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We Live by the Sun

The SCIENCE FOR EVERYMAN Series

OUR ASTONISHING ATMOSPHERE

THE WORLD OF WATER

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ELECTRONS GO TO WORK

VIRUS IN THE CELL

WE LIVE BY THE SUN

SCIENCE FOR EVERYMAN

We Live by the Sun

J. GORDON COOK

FELLOW OF THE ROYAL INSTITUTE OF CHEMISTS

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To MY MOTHER

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Preface

For thousands of years man has been wondering about the sun. Day after day this golden, glowing ball rides through our sky, driving away the darkness and bathing the world in light. It never fails to appear on time, and it shows no signs of growing dim.

Without our regular daily ration of sunlight there could be no life on earth. Light is the source of power that drives all plant and animal bodies. It provides us with the sense of vision and surrounds us with a world of beauty and colour.

The study of light has become a fundamental activity of modern science. We are still measuring the speed of light and estimating the pressure that it causes as it strikes the earth. We are trying to harness it to provide us with the energy we need; and, after a hundred years of practical photography, we are still seeking for an explanation of the way light causes a latent image on the photographic film.

Until quite recently we were happy to think of light in terms of waves which travel through the ether that pervades the universe. But now we have had to think again; in some ways light behaves as though it was a stream of particles. So cunning are the ways of modern physics that these two conceptions have been welded into a coherent theory. Light consists of waves and particles at the same time. No wonder the physicist is regarded with esteem and awe!

I should like to acknowledge with thanks the help given to me by Professor W. E. Curtis, F.R.S., of the Physics Department, King's College, Newcastle-on-Tyne.

J.G.C.

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1

The Riddle of Light

LIFE on earth is lived to a rhythm marked out by night and day. When the sun comes up in the morning living things stir from their sleep; animals forage for their food and busy themselves with the chores of family life; plants unfold their leaves, drinking in the sunshine that powers the manufacturing processes of their living cells. Then, as night comes, activity slows. The world goes to sleep as the sun drags the last of its rays over the edge of the horizon. The light is gone, and the bustle of life is stilled.

The light that controls the rhythm of night and day is so familiar to us that we accept it as we accept the phenomenon of life itself. We know when light is there, and we know when it is not. Yet, when we think more deeply about light we realize how little we really know about it at all.

Imagine trying to explain light to some one blind from birth. There is nothing tangible about it; we cannot describe what it 'looks' like or what it 'feels' like. We cannot define light in any terms that are intelligible to a person who has not experienced it. All we can say is that we recognize light as a sensation that reaches us through our eyes. We simply accept it and are grateful for the world of beauty that it brings.

The philosophers of ancient Greece thought long and deeply about the mystery of light. They recognized some of the peculiarities of its behaviour, but were disinclined to discover anything more by experiment. Empedocles, Aristotle, and Plato all had their views on light, the general

consensus of opinion hardening into a corpuscular theory that matched the early atomic theories of matter itself. Light, according to the ancient Greeks, was a stream of particles emitted by the luminous object. The followers of Plato believed that these particles were sent out by the sun and the eye as well; the phenomenon of sight was due to a complicated reaction that involved these particle streams.

The Greeks recognized that light travels over a straight-line path. The shadow of a building, for example, is outlined sharply on the ground; its pattern is marked out as though the light cut off is travelling in straight lines from the sun.

Also, the Greeks knew something about the reflection of light from polished surfaces. They realized that a narrow ray of light falling at an angle on a mirror was reflected at an equal angle. This, like the straight-line path followed by light, was understandable and fitted in with their theory that light consisted of a stream of particles fired out by the luminous body. The particles were bouncing from the mirror like pebbles from a smooth flat stone.

For a thousand years and more philosophers continued to wonder about the nature of light, explaining its idiosyncrasies as best they could on the basis of the Greek particle theory.

But, in time, difficulties began to crop up. It was found that rays of light are bent as they go from one transparent substance to another. When light strikes at an angle on to a glass surface, for example, the rays do not continue in their original direction inside the glass; they are turned aside and follow a new direction. When they emerge on the other side of the glass they are bent back again as they enter the air; if the two glass surfaces are parallel to each other, as in an ordinary window pane, the light rays are continuing in their original direction again after leaving the glass, although they have been side-stepped a little to one side.

This bending of light as it goes from one substance to another is not so easy to explain when light is regarded as a stream of particles flying out from the luminous source. By the seventeenth century light was playing other strange tricks as well, and many scientists were beginning to have grave doubts about the reliability of the particle theory. During that century the English physicist Sir Isaac Newton took up the study of light and opened the way to our modern understanding of it.

Newton carried out a series of experiments with the help of a glass prism. The prism is a piece of glass of triangular cross-section; its value in the study of light lies in the fact that the sides by which light enters and leaves are not parallel to one another.

Ever since scientists and philosophers had been interesting themselves in light they had been puzzled and intrigued by the effects of glass surfaces cut to form angles one with another. Sunlight falling on the bevelled edges of glass mirrors or on the cut-glass pendants of chandeliers would send out glorious coloured lights. Somehow these cut glass surfaces turned the rays of sunlight into miniature rainbows painted with a range of brilliant colours. Some scientists believed that glass cut in this way was adding something to the light, changing it into coloured rays.

Sir Isaac Newton carried out a series of experiments on this production of coloured rays from light. He passed a beam of sunlight through a prism and allowed the light to shine on a screen after emerging from the other side of the prism. It fell as a continuous band of coloured light: a 'spectrum' formed by all the colours of the rainbow. At one end was a patch of red; then came orange, yellow, green, blue, indigo, and finally violet. The pencil of sunlight entering the glass prism had somehow been changed into a band of coloured lights.

Newton carried the experiment a step further. By putting screens in the way of the light coming from the prism he was able to isolate one coloured ray at a time. Each

colour in turn was then allowed to pass through a second prism. But it was not changed into any new colour-mixture. The rays forming the red part of the spectrum from the first prism, for example, remained as red rays when they passed through the second prism.

Newton carried out a third experiment. He passed a beam of sunlight through a prism and then concentrated the band of coloured light with the help of a lens. He found that the coloured rays merged to form ordinary 'white' light again.

Moreover, if a narrow screen was placed in the path of the coloured rays coming from a prism, so as to block off one of the spectrum colours, and the remaining rays were concentrated again with a lens, the ray of light from the lens would be transformed by a second prism into a spectrum from which the screened colour was still missing. If blue had been blocked by a screen from the original spectrum, for example, it would still be absent when the reconcentrated light was passed through a second prism.

Newton explained his discoveries by assuming that ordinary light coming from the sun is made up of a number of 'pure' light rays, each one causing a definite colour sensation as it reaches the eye. When all these rays are mixed together we get a sensation of 'white' light. When the rays are separated one from another each creates its own appropriate colour sensation.

This splitting of light rays by a prism was explained as being due to the different degrees to which each of the coloured constituents of white light are bent as they pass from air to glass and from glass to air again. The red rays are deflected least, and the violet rays most of all, with the other colours of the spectrum taking up their appropriate positions in between.

This discovery of the composite nature of ordinary light was not easily reconciled with the theory that light consisted of streams of fast-moving particles. But there were other difficulties too.

Christiaan Huygens, a Dutch mathematician, showed that light behaves in a strange way when it is passed through certain types of crystal. A narrow beam of light shining through a crystal of Iceland Spar is split into two separate beams which emerge independently at the other side of the crystal. It is as though the crystal could bend the light through two distinct angles, splitting the ray into two forms of white light differing in their 'bendability' from one another.

With these discoveries remaining unexplained things were becoming difficult for the light-particle theorists during the seventeenth century. But there is another phenomenon too, which Newton studied in great detail. This is the effect of thin layers of solid or of liquid films on light. When a beam of light falls on to a sheet of very thin solid, such as mica, it forms coloured concentric rings or bands. This effect is often shown by soap-bubbles and by an oil film floating on the top of water. How can these patterns of light and shade and colour, formed simply by light falling on thin layers of solid or liquid, be explained by thinking of light as streams of particles?

During the seventeenth century Christiaan Huygens extended and improved an alternative theory of light which had been put forward tentatively by other scientists. Huygens could not see how it was possible for two rays of light 'particles' to cross each other without bumping and knocking each other sideways. Yet beams of light did not seem to affect one another in this way. Light, maintained Huygens, cannot consist of particles at all. It is a system of wave motions that move forward from the source, like ripples caused by a stone falling into a pond.

Newton, however, was not convinced. If light was nothing but waves, he said, why did it not spread out when shone through a hole? Light from a hole travels as a definite ray or 'jet'; but waves of water passing through a narrow opening will spread out to form a semicircular wave front on the other side.

By the end of the seventeenth century the controversy had not been resolved. The corpuscular theory of light, sustained by the immense influence of Newton, remained in favour. But Huygens' wave theory had established itself.

For a hundred years the corpuscular theory of light struggled to survive against the evidence of experimental facts. During the early nineteenth century it became apparent that only by regarding light as waves could much of its peculiar behaviour be explained.

But the problem still remained—waves of what? Light could not be considered as waves travelling through any material substance. It made its way for countless millions of miles through empty space as it travelled earthward from the sun and stars. The waves of light must undulate in some mysterious medium that permeates the emptiness and the material objects of the universe alike. So came the conception of the ether—the all-pervading, matterless substance that enables light and other influences to travel through space and through material things.

In 1865 Clerk-Maxwell developed his theory of electro-magnetic waves; he believed that electric currents oscillating to and fro along a wire, for example, would stimulate a corresponding vibration in the ether. He called these vibrations electro-magnetic waves. Intangible and invisible, they were regarded as pulsations of electro-magnetic influence radiating from the region in which the electric current is oscillating. In 1887 Hertz proved that electro-magnetic waves were created by an oscillating current, just as Clerk-Maxwell had predicted. From Hertz's discovery have come the radio and radar, television, and other electronic industries that we accept as part of everyday life to-day.

These electro-magnetic waves produced by oscillating currents were found to travel through space at a speed identical with that of light. And it became apparent that they resembled light in almost every way. Light, in fact, was simply a particular form of electro-magnetic wave

which happened to stimulate the retina of the human eye.

Nowadays we have accepted this theory of light as an electro-magnetic undulation that travels through space. We do not know exactly what these electro-magnetic waves are, nor do we really understand what we mean by space. But we recognize that some assumptions and acceptances must be made if any theory of this sort is to be sustained.

Light has now been brought into line with all the other electro-magnetic waves that play such a big part in modern affairs. These waves have been organized into a broad spectrum on the basis of the length of the waves; that is to say, the distance from one wave 'crest' to another. At one end of the spectrum are the short-wave gamma rays emitted by radio-active substances, with wave-lengths less than one thousand-millionth of an inch; at the other end are the radio waves, undulating in wave-lengths measuring as much as a mile. Visible light comes as a short band in the electro-magnetic spectrum, sandwiched between the ultra-violet waves and the waves of radiant heat. The wave-length of visible light lies between about sixteen and thirty-two millionths of an inch.

Unlike sound waves travelling through the air, which pulsate to and fro in the direction in which the sound is travelling, light waves vibrate *across* the direction in which the light is moving. They are like the undulations in a stretched rope that is raised and lowered at one end.

All that distinguishes light waves from other electro-magnetic waves is the wave-length. Like radio waves and heat waves, radar waves and X-rays, light travels through space at a speed of about 186,000 miles a second. This is the speed at which a wave-crest is moving forward from its source.

At the beginning of the present century the wave theory of light had been developed to the point where it appeared to satisfy all requirements. It explained the well-known phenomena of light behaviour and provided a basis for the

mathematical interpretation of light. Light had settled down into its allotted space in the spectrum of electromagnetic vibrations.

But since then things have begun to go wrong. Light has been found to have properties that are not easily explained in terms of waves. To start with, light travels at tremendous speed through empty space. If it is travelling as waves, then waves of what? It is all very well to assert that there is an all-pervading, mysterious ether that carries electromagnetic waves through space, but this is in some ways a contradiction in terms.

When light falls on to certain metals it creates a flow of electricity; this electric current consists of electrons which have been dislodged by light from the atoms of the metal. The relationship between these liberated electrons and the light which sets them free can only be explained if light is regarded as particles rather than as waves.

So we now find it necessary to return to the particle theory that was discarded more than a century ago. Light is in the peculiar position of being a bit of both; in certain circumstances it is regarded as waves, and in others as particles. At first sight the two conceptions might appear to be fundamentally opposed one to another. But the two have been reconciled and combined to provide a reasonably satisfying theory.

Light is now believed to be delivered in packets of definite size depending on the wave-length. When light strikes the metal of a photoelectric cell each packet, or 'quantum,' of light energy can release an electron from an atom that it strikes. The number of quanta reaching the metal is determined by the amount of light striking it; the size of the quanta is fixed by the wave-length of the light.

In the normal way we cope with immense numbers of quanta in our dealings with light. In a second a candle will throw out something like one million million million quanta of light. When we describe the behaviour of these vast numbers of particles we can do so only on a basis of

average behaviour. We cannot consider individual quanta at all.

The electro-magnetic waves that are so useful in explaining the behaviour of light can therefore be considered as waves that describe the way in which astronomical numbers of light particles will be found at any instant. They are probability waves, which mark out the distribution of light energy.

The particle of light energy involved in these waves is called a photon. Photons acting in countless billions form electro-magnetic waves we recognize as light. Nobody has seen a photon, nor is there any direct proof of its existence. But in a world where everything has become little more than a complex system of electro-magnetic waves cum particles of nobody-knows-quite-what photons have as much right to a possible existence as anything else.

2

The Sun—Our Personal Star

THE darkness of night is dissolving in light that flows steadily across the sky. Over the eastern horizon a curved shoulder of fire appears; our sun has arrived, bringing with it another day of glorious light.

In days gone by man worshipped the sun. It brought light, and so gave the world life. There are still many primitive people who look on the sun as the home of their gods.

As the source of our light, the sun features large in man's picture of the universe. Yet, in spite of its immediate importance to us here on earth, the sun is only a fairly average specimen of star. It is one among millions. And, as stars go, it is not particularly big. Nor is it unduly small.

Compared with our earth, which is merely one of many satellites spinning round it like moths around a flame, the sun is large indeed. The Earth measures about 25,000 miles around its middle; the sun's girth is more than 2,700,000 miles. Its volume is over a million times the volume of the earth.

The gravitational attraction of this enormous mass of matter holds the Earth in its orbit, 93 million miles away. Together with the other planets, and countless smaller bits of matter, we gyrate round and round the sun, bathing in its life-giving light. We are part and parcel of the solar system, living on an insignificant satellite that gyrates round a mediocre star.

Until 1610, when Galileo focused his first telescope on

the sun, we knew little about our own personal star, other than the fact that it obviously gave us light and heat. For three hundred years astronomers have been peering at the sun, trying to find out something of its detailed appearance and behaviour. In the last twenty years progress has been rapid, and we now know sufficient to realize that the sun's mysteries may keep us guessing for thousands of years to come.

Not so long ago the sun was believed to be a 'ball of fire.' It was a great mass of burning fuel floating in the sky. We now know that this cannot possibly be true. The sun is a globe of incandescent matter, heated to temperatures so high that they are meaningless to us here on earth.

The sun is spinning like a top on its own axis, rotating from east to west. But it does not spin uniformly, like a solid ball. The sun's equator makes a circuit in about twenty-five and a half days. Nearer the poles the time of rotation increases; the 'polar regions' of the sun take nine days longer to revolve. If the sun was solid each part of it would take the same length of time to make its circuit; but it is a gas, and its middle can rotate faster than its poles.

The sharply defined edge of the sun, which we see by looking at it through dark glasses or through a telescope, is called the photosphere. This is a layer of gas, estimated at 200 miles thick, which controls the light and other radiations reaching us from the sun.

The outer edge of the photosphere is the coolest part of the sun; yet it is at a temperature of about 5000°C. Inside the sun the temperature rises rapidly, reaching perhaps 20 million degrees in the deep interior. Even so, the sun is cool by comparison with other stars. Some are believed to rise to temperatures in the region of 40 million degrees.

In the outer layers of the sun's photosphere the gases are so tenuous that the pressure is only one-hundredth of that exerted by the earth's atmosphere at sea level. These hot, thin gases forming the sun's outer edge are glowing faintly

and are transparent to the light coming from the lower levels of the photosphere. Two hundred miles lower down, at a depth which we regard as being the base of the photosphere, the pressure has increased and is about one-fifth of the earth's atmospheric pressure. The gases here have become opaque; they act as a barrier to radiations coming from below, transforming them into the light which is emitted into space.

Although the sun is covered by this flimsy layer of hot gas forming the photosphere, we still see the outline of the sun as a well-defined edge against the sky. The depth of the photosphere, 200 miles, is large by everyday standards here on earth. But by comparison with the sun itself, and at a distance of 93 million miles, it becomes insignificant. Two hundred miles at such a distance is comparable with the thickness of a human hair at thirty yards.

The sun looks darker towards the edges than it is in the middle. We do not see so far into the sun's interior when we are looking at its edge. The depth from which the light comes is at a lower temperature when the rays have to travel slantwise through the photosphere to reach us; the light is therefore not so bright.

The entire surface of the sun is covered with a mottled pattern that changes constantly from one minute to another. A layer of gas inside the sun is in continual movement; the gases of this layer surge upward bringing energy from below and dispersing it nearer the surface of the sun. As the lumps of gas float upward cooler gas sinks down to take its place. These billowing clouds of submerged gas cause the mottled surface of the sun.

The composition of the matter in the sun has been studied by examining the wave-lengths of the light that reaches us as sunshine. Sixty-six of the ninety-two elements that we find on earth are known to be present in the atmosphere of the sun. Most of the other twenty-six elements are found on earth in extremely small amounts; it is unlikely we should be able to detect them in similar

amounts on the sun. The proportions of the sixty-six elements in the sun's atmosphere are roughly the same as we find in the crust of the earth. Hydrogen and helium are the exceptions; they are vastly more plentiful on the sun than they are on earth. One-third or more of the mass of the sun is believed to be hydrogen.

At the temperatures which exist even on the sun's outer surface atoms of the elements forming the sun's matter are in a state of violent agitation. They cannot join up one with another to form compound atoms, or molecules, such as they do in the chemical changes that give us all the different substances we find on earth. There are few, if any, molecules on the sun; the atoms stay single.

Inside the atoms themselves the high temperatures of the sun play havoc with the internal arrangements of the sub-atomic particles. Each atom is a solar system on its own account, with tiny electrons circulating in orbits round a central core or nucleus. At high temperatures the electrons are shaken loose from their atoms. At the base of the sun's photosphere this disruption of the atoms is so intense that there are 1000 million million free electrons to every cubic inch. These unattached electrons have escaped from agitated atoms, particularly from atoms of metals in which they are less tightly held than in other elements.

The break-up of individual atoms continues with increasing vigour towards the centre of the sun. Agitation of the atoms becomes more violent as the temperature increases, and the particles are subjected to mounting pressure as they are overlaid by more and more matter above.

Inside the sun all the circulating electrons have been stripped from their parent atoms. As these electrons determine the chemical differences between one atom and another, the sun's core is little more than a mass of nondescript matter. Electrons, protons, neutrons, and other sub-atomic particles are crushed together into a hodge-podge of nuclear mush. The ordinary relationships and distances

that control the organized atoms are squeezed out of existence by fantastic pressures, estimated at 1000 million tons to the square inch.

The density of the squashed-up matter of the sun's core is so great that it is ten times as heavy as lead; one cubic foot would weigh about three and a half tons. Resisting this enormous gravitational pressure, immense forces are constantly pushing outward from the centre of the sun.

As energy is produced continually inside the sun, temperature and pressure would rise to bursting point if nothing relieved the strain. But the sun sloughs off some of its surplus energy by the simple act of expansion, which relieves the internal pressure and temperature. The expansion mechanism operates automatically; the sun is constantly swelling and shrinking with a pulsation too small to be seen even with our most sensitive telescopes.

The sun has another safety-valve that sets free some of the energy building up inside it. Clouds of dense nuclear matter float up from the overburdened core, carrying away some of the energy and cooling the hot interior. The rising lumps of energy-packed gas are replaced by cooler matter that sinks inward, eventually to be compressed and heated in its turn.

These clouds of atomic pudding released by the core are in the over-compressed state that is characteristic of the matter forming the inside of the sun. The individual particles are pushed closer together than they are in their normal atomic arrangements. As they rise toward the surface their surroundings are becoming cooler. A point is reached eventually at which the atomic particles begin to collect electrons round them and resume the sort of form that they prefer. They are on the way to becoming normal atoms again, and they strive to attain their proper design and distances apart. At this stage the clouds of matter undergo tremendous expansion, surging through the photosphere like mammoth geysers spurting from the hot interior of the earth.

These huge eruptions breaking through the outer surface of the sun are believed to be responsible for the sunspots, strange dark patches on the surface of the sun which have puzzled scientists for centuries.

Chinese astronomers were studying sunspots with the naked eye in A.D. 200. But it was not until Galileo examined them through his telescope in 1610 that general interest was aroused. Galileo proved that they were, in fact, dark patches on the surface of the sun itself and not shadows cast by other bodies. They changed their shapes and sizes as they moved from east to west across the surface of the sun.

For two centuries after Galileo's discovery little more was learned about sunspots. Then in 1826 Schwabe, a German apothecary, began a systematic study of sunspots which he continued for half a century. Schwabe examined the sun through his telescope every day and noted the size, appearance, and positions of all the sunspots on its surface. By 1843 Schwabe had established that there was a rhythm in the intensity of sunspots; the area of the sun covered by them reaches a maximum, on average, every 11.2 years. The actual length of time between each period of maximum sunspot activity may vary between eight to thirteen years. But taken over a long period of time the average is 11.2 years.

During the last hundred years Schwabe's discovery of the sunspot cycle has been confirmed beyond all doubt. During the years of peak activity the sun's radiation increases, and the effect is noticed on earth in many ways. More water is evaporated from the sea, and rainfall is heavier in some parts of the world. Glaciers melt more quickly, and ice from the polar ice caps breaks away to send more icebergs floating into the Atlantic. The change in climate affects the growth of vegetation during peak sunspot years, and with more plant food to eat the number of animals increases too.

This rhythmic sunspot cycle has left its mark in the rings

of tree trunks; every eleven years, on average, the growth rings are more pronounced. The effect has been detected in fossil tree trunks dating back for hundreds of thousands of years.

Sunspots appear almost entirely in an equatorial region of the sun between about 30° latitude north and south of the equator. They never appear in the higher latitudes nearer the sun's poles. At the beginning of the eleven year cycle spots form in the high latitudes of the equatorial sunspot band. Then, as the sunspot cycle approaches its maximum the spots begin to appear nearer and nearer to the equator. Finally, in the closing years of the cycle the spots appear close to the sun's equator. These tail-enders of the cycle are often overlapped by the first spots of a new cycle appearing in the higher latitudes of the sunspot band.

Although there is this eleven year cycle of activity, variation within the cycle is so great that it is not possible to predict where spots will come on the sun or when they will arrive. Nor is it possible to forecast the size or numbers of spots expected at any time.

Usually sunspots appear in groups, often in pairs. One spot of a pair will trail along beside and slightly behind the other; then, as the pair moves across the sun the rear spot will catch up with the leader.

Some sunspots are only a few hundred miles across and last for a day or less. Others are 50,000 miles or more in diameter, big enough to envelope the earth; they may last for several months. In February 1944 a sunspot photographed at Greenwich Observatory covered an area of 6000 million square miles.

Though a large sunspot is seen by the naked eye as a black patch on the sun, the telescope shows that its structure is more complex. Surrounding the dark interior of the sunspot is a border of lighter material, separating the dark spot from the bright surface of the sun itself. The darkness of the sunspot is purely relative. It is cooler than the sun's surface and therefore appears dark by comparison. But

the temperature of a sunspot is about 4000°C. compared with 5000–6000°C. in the photosphere of the sun.

Surrounding a sunspot or a group of sunspots are patches of surface brighter than the rest of the sun. These intensely hot regions are responsible for some of the extra radiation that reaches the earth during periods of sunspot activity. They more than make up for the loss of radiation due to the lower temperature of the sunspots themselves.

Vast, swirling movements have been seen in the filaments of flame near sunspots, and the rhythm of sunspot activity is accompanied by a rhythm of change in the electrical and magnetic properties of the earth. These changes are caused by emission of radiations and jets of high-speed particles from the vicinity of the sunspots, which affect the electrical status of the earth's atmosphere.[1]

This upsurge of activity in the sunspot region has been studied in detail during recent years. New techniques have been developed which enable us to watch more closely than before what is happening on the surface of the sun. In particular we can study the huge flames and flares that shoot out from the sun, reaching into space for hundreds of thousands of miles.

In 1859 the British astronomer Carrington saw the first solar flare coming from the vicinity of a sunspot. Watching a group of sunspots, he noticed two patches of intensely bright light which flared and disappeared again in a few minutes. Carrington noticed that the bright flare was accompanied by disturbances in the earth's magnetic field; a moderate disturbance took place at the same time as the flare, and a much more intense one some sixteen hours later.

These vast flares are now commonly associated with areas of sunspot activity. Vast clouds of flaming gas are suspended over sunspot regions, twisting and turning over hundreds of thousands of miles of the sun's

[1] See Chapter 14 of *Our Astonishing Atmosphere*, another volume in this series.

surface. Suddenly the whirling flame will go plunging back into the sun at speeds of 200,000 miles per hour. Sometimes a solar flare will reach up from one side of a group of sunspots, wheeling back into the sun at a point 30,000 miles away. A huge arch of swirling light is raised over the sunspot area, perhaps to break up and fall in confusion into the sun after only a few minutes.

When the sun is marked with many spots flares will break out at a rate of one every two days. Some of them are enormous explosions of gas such as the famous one of July 26, 1946, which raged like a tornado across nearly half a million miles of the sun's surface. But most of the flares are smaller and can be seen only with difficulty against the bright photosphere. During times of total eclipse, when the sun's surface is blacked out by the moon, solar flares can be seen as they surge out from the edge of the sun.

Above the photosphere, the sea of incandescent gas which forms the visible surface of the sun, there is a mantle of thin-spread gas some 5000 miles thick. This is the chromosphere, in which calcium, hydrogen, and other atoms, stripped of some of their circulating electrons, are believed to exist in a state of violent motion. In the chromosphere the atoms behave in some respects as though gravity was in abeyance; some strange force supports them and protects them from the fierce attraction of the sun itself, which ought to drag them down into the interior.

In keeping with the rest of the sun the matter forming the chromosphere becomes cooler with increasing distance from the interior. But at a certain point there is a change in the rate of fall of temperature. The gases begin to get hotter, until in the upper chromosphere they are at a higher temperature than in the layers below. Estimates have put the temperature at between 10,000 and 30,000° C., compared with 5000° C. for the temperature of the top layer of the photosphere.

Cutting through the chromosphere are walls of flaming gas that soar to heights of 50,000 miles or more. When the sun is eclipsed these prominences can be seen as huge walls of gas hundreds of thousands of miles long. Often the prominences will hang above the chromosphere for days without change. Sometimes the suspended matter will flow back towards the sun at great speed or float like mammoth clouds outside the chromosphere.

Not all the sun's prominences are so serene; some will shoot out to heights of 150,000 miles above the chromosphere, only to slide back gracefully into the sun. Occasionally a great lump of gas will explode with such violence that huge clouds of incandescent matter are blown out into space.

During an eclipse the sun can be seen to have an extensive 'upper atmosphere' that reaches out for a million miles. This is the corona, a glowing halo sending out a light so dim that it cannot be seen when the sun itself is on view. It has been suggested that the corona consists of clouds of electrons moving at speeds of about seven million miles per hour. The temperature of the corona has been put at a million degrees.

What makes the corona so hot? It may be that there is some leakage of overheated matter from great depths in the sun's interior. Possibly, the corona is a storehouse of atomic debris resulting from the nuclear disintegrations that take place on the sun.

In 1930 a young French astronomer, Bernard Lyot, built a special type of telescope in which the sun was artificially eclipsed. Lyot carried his telescope to the top of the 9400-foot Pic du Midi, in the Pyrenees, where the air was pure and clear. Here he studied the corona of the sun for the first time without having to wait for an eclipse. Since then 'coronagraphs' have been built in many parts of the world, and much of our knowledge of the sun has been acquired with their help.

The shape of the corona changes with the sunspot cycle.

The inner corona, about 100,000 miles above the photosphere, forms great arch-like structures over regions where sunspots are active. As the time of sunspot minimum approaches the corona changes its shape, contracting above the sun's poles and spreading out above the equator. Short curved rays can be seen inside the pearly, greenish glow.

During the eclipse of June 1954 the corona was seen to extend for two million miles beyond the sun. The total radiation from the corona amounts to only a few millionths of that from the sun; it is equal to about half the light from the full moon. But with the sun blacked out the corona can be seen distinctly in the sky.

At times of total eclipse long streamers of light have been seen extending from the sun. This ' zodiacal light,' as it is called, is too faint to be seen even when the sun itself is eclipsed. The corona is bright enough to ' drown ' the zodiacal light. But it can be detected when the eclipsed sun is below the horizon. The earth blacks out the corona, and the zodiacal light can be seen. The source of this light is unknown. Like so many of the phenomena we associate with the sun, it is a mystery that has yet to be solved.

3

A Cauldron of Light

THE sun sends out a glorious mixture of radiations that we recognize as sunshine. Some oscillate with dignity, like the hills and valleys of the ocean swell; others are vibrating fussily, like the tiny ripples that are raised on water by a puff of wind. But only those waves between sixteen and thirty-two millionths of an inch in length are able to stimulate the cells in the retinas of our eyes. These are the visible rays we describe as light.

The source of all these waves of radiation lies in the atoms that form the matter of the sun. Atoms are no longer the indivisible, inert particles that they used to be; they are in turn made up from smaller particles. Each atom has a central core, or nucleus, around which tiny electrons circulate at terrific speed.

In any atom at any time electrons revolve in definite orbits round the nucleus. As a rule the electrons settle in orbits close to the nucleus, keeping up their rhythmic movements round and round. In this state the energy of the atom is at a low level. But if extra energy is made available the electrons may jump to orbits farther away from the nucleus. Eventually, if sufficient energy has been poured into the atom the electron may escape completely, leaving an electron-short atom or 'ion.'

According to modern theories, energy is absorbed and emitted in bundles of definite size, called quanta. Quanta are like atoms of energy. When an atom is absorbing energy it does so by accepting quanta that enable its elec-

trons to jump from one orbit to another farther from the nucleus. Each electron jump needs just the right bundle of energy to take it from one orbit to another; too much is no good, nor is too little. The quantum must be exactly right. An atom is like a slot machine that accepts only the proper coins.

The hydrogen atom, simplest of all, has a single electron circulating round its nucleus. All other atoms have more than one; uranium, biggest of all naturally-occurring atoms, has 92. The quantum of energy associated with electron jumps from one orbit to another varies as between different orbits within an atom and between atoms of different elements. Every atom lays down a list of quantum sizes that will enable its electrons to make their orbital jumps. This list of quantum sizes is a characteristic of the atom of every element. Hydrogen accepts energy in quanta of certain sizes; iron accepts a different range, and sulphur another.

When atoms have been provided with energy that enables their electrons to jump outward from one orbit to another they are in an 'excited' state. The absorption of suitable energy quanta has allowed electrons to move farther away from the nucleus; but by discarding energy the electrons can reverse the process, returning to orbits nearer the atomic nucleus. And the energy is emitted in quanta similar to those which were absorbed. This is the energy which we identify as light.

When any form of matter is giving out light it is sending out streams of quanta of definite sizes. The sizes of the quanta depend upon the structure of the atom that is emitting them.

In the modern theory of light these streams of quanta behave as waves, and the wave-length depends on the size of the quanta.

What this all means, therefore, is that any atom which has been stimulated by extra supplies of energy may emit light as its electrons return towards the nucleus leaping

from one orbit to another on the way; the light is emitted in a series of distinct and definite wave-lengths that are controlled by the interior design and structure of the atom itself.

When a substance is in the form of a gas its atoms are moving freely. Now and again they will collide and disturb each other. But for the most part every atom can operate as an individual. When a gas is stimulated, for example by heating it or by passing an electric current through it, the electrons in its atoms will jump outward into orbits farther from the nucleus. And as they jump back again they will emit light in the form of waves of definite length.

Atoms of sodium, for example, vaporized in a hot gas flame will emit light waves in two wave-lengths. Passed through a narrow slit and then through a glass prism, this light does not split up into a spectrum of different colours, as sunlight does. It forms two separate lines of light in the position corresponding to the yellow part of the spectrum; the wave-lengths of the lines are so close together that they can be distinguished only with difficulty one from another.

In the same way atoms of other elements emit light in their own characteristic wave-lengths. Strontium vapour sends out some light in the red part of the visible spectrum and some in the blue. Strontium vapour therefore glows with a crimson colour. Iron, which emits waves corresponding to many regions of the spectrum, appears white; thallium sends out a single wave-length which we recognize as green.

These light radiations coming from a luminous gas are characteristics of the atoms forming the gas. Each element has its own individual design of electrons in its atom and sends out a pattern of light controlled by this atomic design. The wave-lengths of the light emitted by the vapour of an element can identify the element as surely as a set of fingerprints will identify a human being.

With the help of a prism or a diffraction grating[1] light can be split into its constituent radiations of different wave-length. A narrow beam of the light, formed by passing it through a fine slit, is allowed to fall on the prism; as the light passes through the prism it is bent through angles that depend on the wave-lengths of the constituent radiations. Emerging from the prism, the separated rays each make a line of light in the appropriate position on a screen; by measuring the angle through which the light has been bent we can identify its wave-length.

Modern optical instruments enable us to analyse light from any source in this way; we can separate and identify the radiations of different wave-lengths that it contains. And by comparing the light patterns with those known to be given by various elements we can identify the substances that are emitting light.

This technique of 'spectrum analysis' enables us to detect elements in extremely small amounts; an ounce of impurity in 100 tons of iron will betray its presence when light emitted by the vaporized iron is analysed.

Although the light pattern emitted by excited atoms is so precise when they are wandering freely as a gas, the composition of the light changes as the atoms crowd together and come under each other's influence. In a solid the atoms have given up their freedom and are anchored close to each other. The vibrations of one atom affect those of its neighbours. Instead of radiating their light in a few well-defined wave-lengths the atoms emit light as a medley of radiations covering a wide range of the spectrum.

At ordinary temperatures solid substances do not emit waves that are detectable by our eyes. They reflect waves falling on them, but they do not generate light waves on their own account. They are not luminous. When a solid, such as a piece of iron, is heated the vibrations of its atoms are affected. Atomic movement becomes more vigorous as the temperature rises. And the hotter the iron gets, the

[1] See Chapter 10.

shorter do its radiations become. Eventually, at 500–600° C., the waves have become so short that they are just becoming visible. We see a dull red glow coming from the heated iron; it is sending out red rays, the longest rays of the visible spectrum.

As heating continues the light waves emitted by the iron become shorter and shorter. The metal begins to glow with a whiter light and is eventually tinted blue as the radiations enter the short-wave region of the spectrum. As the temperature rises further the radiations become so short that they leave the visible region again. The atoms are sending out ultra-violet rays in addition to the rays of visible light.

It is a strange fact that the wave-lengths of the light rays emitted by a heated solid depend only on the temperature and not on the nature of the substance itself. A lump of stone inside a red-hot furnace is indistinguishable from a piece of metal; both are at the same temperature and are sending out the same light rays.

Unlike the light from a glowing gas, the light from a heated solid forms a continuous spectrum. As the temperature rises the solid emits shorter and shorter rays. But these do not take over from the longer rays already being emitted; they are superimposed upon them. Increasing the temperature merely extends the range of wave-length of the radiations by introducing shorter ones.

The light from a glowing solid passed through a prism is separated into a spectrum of colour composed of light of innumerable wave-lengths. If the temperature of the solid could be raised to 6000°C, similar to that of the sun's photosphere, the light emitted would be daylight.

The emission of light in definite wave-lengths by atoms of a luminous gas is a consequence of the natural vibration rhythms existing in the atom. These rhythms also control the absorption of light falling on to the atom; as might be expected, the wave-lengths of light that any substance accepts are the same as those it emits. An atom is 'tuned'

to deal only with light of definite wave-lengths, whether it is emitting or absorbing.

When common salt is held in a hot gas flame the flame glows yellow as the sodium of the vaporized salt emits its characteristic light. Light from the flame passed through a narrow slit and then through a prism throws two yellow lines close together on a screen. If an arc-light is arranged behind the sodium flame white light from the incandescent carbon shines through the sodium flame and enters the slit. This light, coming from a glowing solid, consists of a mixture of wave-lengths; it is split into a band of coloured lines making up a continuous spectrum. But in the place where the sodium threw its yellow lines there are now two black lines. The atoms of sodium in the flame have absorbed radiations from the white arc-light corresponding in wave-length to those that they emit on their own account.

This selectivity of atoms for certain types of light is similar to the selectivity of a radio set. Programmes are sent out by a radio station and carried through the ether by waves of a definite length. If a receiving set is adjusted so that currents of electricity will oscillate in 'tune' with the oscillations of the radio waves the set will absorb the waves which can be made to operate the loud-speaker. But if the receiver is not adjusted to oscillate in tune with the radio waves it does not absorb them.

The fact that a receiver also sends out its own waves enables us to carry the analogy still further. Properly tuned, a receiver will absorb waves from the ether. By so doing it removes some of the energy carried by the waves, so that the strength of the vibrations is weakened after they have passed over the receiver.

As the receiver oscillates in response to the waves it has absorbed it emits waves similar to those it has picked up. But the emitted waves do not make up for those that have been removed in the first place; the receiver is sending out its waves in all directions round it, whereas it absorbed

waves travelling across it in a direction away from the transmitter. The total strength of the waves travelling outward from the transmitter and across the receiver is still not equal to their original strength.

It is the selectivity of a radio receiver that enables us to pick out the programme we prefer. Each radio station sends out its programmes on waves of a definite length. The ether is crammed with a mixture of waves as diverse as light waves in the sunshine. But by tuning the receiver we adjust it to absorb vibrations of the particular wavelength we want. It picks these waves from the mixture that reaches it, just as an atom will absorb the light rays to which its natural vibrations are attuned.

Inside the sun atoms of hydrogen, helium, and other elements are squashed together under tremendous pressure and are in a state of violent agitation. They influence each other to such an extent that light emitted by the sun is a complex mixture of waves. Sunlight passing through a prism is spread into a continuous spectrum. If a narrow beam of sunlight is formed by passing it through a slit, and this beam is allowed to fall on to a prism, the spectrum consists of a succession of lines of light. Each line is an image of the slit which is thrown by light of a definite wave-length, bent to a precise angle by the prism.

Sunlight can be spread out by a succession of prisms or diffraction gratings to form a spectrum with a total width of hundreds of feet. A permanent record of the position and brightness of every region of the spectrum can be made by letting the light fall on to a photographic film. Although the sun provides us with a spectrum of light that is formed virtually from a continuous band of wavelengths, there are in fact many black lines in the sunlight spectrum. These lines represent blank spaces in the wavelength mixture; they are radiations that have been removed from the mixture of light during its journey from the source in the sun. They are formed in the same way as the black lines in the spectrum thrown by white light

passing through the sodium flame. And by examining them closely we can identify the elements that have caused them.

Some of the black lines in the sunlight spectrum correspond to the wave-lengths of light emitted by gaseous hydrogen and helium, calcium, and other metals. There are no clouds of luminous vapours of these elements in the atmosphere of the earth, or in space between us and the sun. Absorption of the light must have taken place on the sun itself. It is believed that most of the light absorption is done by gases in the sun's chromosphere. Thousands of lines have been identified in the spectrum and recognized as the characteristic absorption lines of many elements.

Among the elements found in the sun's atmosphere is the light-weight metal lithium. This discovery of lithium, albeit in mere traces, has given support to the belief that there is little mixing between the matter of the sun's interior and the surface layers.

Lithium atoms are extremely sensitive to nuclear collision. Inside the sun they could last for only a few minutes before being blasted by fast-moving particles. The lithium atoms in the sun's atmosphere cannot have spent any length of time inside the sun itself, or they would have been destroyed. They have probably stayed in the sun's atmosphere since the sun was created thousands of millions of years ago.

When atoms are brought to a state of violent agitation at high temperatures electrons will jump so far away from the nucleus as to escape entirely. The part of the atom that is left, including the nucleus and the remaining circulating electrons, is an ion.

The loss of electrons in this way upsets the balance of vibrations inside the atom. The wave-length pattern of the light radiations that the atom will absorb is altered; an ion has a different spectrum to the atom from which it has been formed. Analysis of the black lines in the sun's spec-

trum therefore tells us not only what elements the light has passed through, but supplies information about the state of their electrons and their temperature and density as well.

At times of total eclipse the brilliant photosphere of the sun is hidden by the moon. It is a strange coincidence that the moon is just the right size to black out the sun's disc; the chromosphere and prominences, the flares and corona, can all be seen when the moon cuts off the direct rays of the sun. When this happens the spectrum of light undergoes a dramatic change. As the sunlight fades the black lines disappear and are replaced by bright lines occupying the same position on the spectrum.

These bright lines are light that is being radiated by the luminous gases of the chromosphere. Normally the gases are absorbing light of characteristic wave-lengths from the sunlight. With the sunlight cut off, we see only the light emitted by the gases in the same wave-lengths.

When we photograph the sun in its own natural light all the constituent rays leave their mark on the film. The picture is a composite one that derives from light leaving innumerable different sources in the sun. But much of our most up-to-date information about the sun has been obtained by photographing it in light of a single wave-length.

If sunlight is dispersed to form a spectrum a shield can be arranged with a slit in it coinciding with one of the black lines on the spectrum. The limited amount of light coming through the slit is light emitted by one of the elements on the sun. And by using this light only to photograph the sun we can obtain a picture which shows the distribution of this particular element at varying depths below the sun's surface. A photograph taken in light corresponding to one of the black lines due to hydrogen, for example, shows how hydrogen is distributed on the sun.

Photographs of this sort show the prominences as filaments of light on the sun's surface; sunspots and the turbulent regions surrounding them are pictured in fine detail. Isolated clouds of calcium and hydrogen are seen

floating in the chromosphere as though defying the gravitational attraction of the sun. Both these elements appear at great heights above the surface. Photographed in calcium light, the chromosphere has a mottled, orange-peel appearance. The turbulent atmosphere of the sun extends for 5000 miles and more above the surface.

Any light trying to escape from inside the sun stands little chance if its wave-length coincides with any of the black lines in the sunlight spectrum. Even if a quantum of light of this sort should make its way through the 200-mile-thick photosphere it would be snapped up by atoms in the layers above. The rarified gases of the chromosphere, transparent to quanta of light that do not correspond in wave-length to any of their absorption lines, are opaque to quanta that meet their requirements.

Analysis of light from the sun's corona shows lines that do not correspond with those emitted by any atoms known on earth. These lines are caused by atoms stripped of many of their planetary electrons; brightest of all the corona lines consists of light emitted by atoms of iron from which thirteen of the twenty-six circulating electrons have escaped. Other lines from the corona come from nickel atoms with only fourteen of their twenty-eight electrons remaining.

Ions of this sort can be produced only by the most violent treatment of atoms. It is difficult enough to knock one electron from an atom. But the difficulty becomes progressively greater when we try to remove more. To remove as many as thirteen the atoms must be in a state of extreme agitation, such as would be found at temperatures approach 1,000,000°C.

This is the sort of temperature that exists in the pearly corona of the sun.

4

Nature's Atomic Furnace

THROUGHOUT the twenty-four hours of every day the sun is sending out its light. When darkness falls over our own particular town or village the sun has not closed down for the night; it is shining with undiminished vigour on the other side of the earth.

For at least 1000 million years the sun has kept up its output of light with only slight fluctuations in intensity. Fossils of creatures that lived in these far-off days tell us that the sun was shining then just as it does to-day. The temperature of the sun's photosphere has changed little over this immense period of time. And it seems likely that the sun was shining just as steadily during the previous 1000 million years as well.

For all this time the sun has been sending out heat and light at the rate of half a million million million million horse-power a second. This enormous outflow of energy is more than a million times the amount of energy stored away in the earth's reserves of coal and oil combined. It has been emitted by the sun during every second of the last 2000 million years. This energy must come from some virtually inexhaustible source inside the sun. It must be produced either by the transformation of other kinds of energy into heat and light or it must be created afresh by the annihilation of matter.

The philosophers of old believed that the sun was a ball of fire; it was a mass of wood or coal or other fuel that burned in the sky just as these fuels burn in a furnace here

on earth. The heat and light radiations emitted by a fire are energy that has been held as chemical energy inside the substances of the fuel. When a coal fire burns carbon atoms in the coal are uniting with oxygen atoms from the air to form complex atoms, or molecules, of carbon monoxide or carbon dioxide gas. Whenever atoms join up to form molecules or change about from one molecular union to another there is a disturbance in the energy-balance between the atoms. Energy that is left over from a chemical change is released in the form of light or heat.

Calculations have proved that the sun could not possibly release the amount of energy it does as a result of chemical changes of this sort. Even if the sun was an enormous lump of pure coal the energy emitted as it burned would be only one five-hundred-thousandth of the radiation that is actually produced. The rearrangement of atoms into different molecules results in comparatively small energy changes.

In any case it is now known that the sun's temperature is so high that atoms cannot remain attached to one another to form molecules. The vibrations are so violent that the sun is a mass of individual atoms and pieces of atom; only a few simple atomic unions are believed to be possible in the sun's inferno.

With ordinary burning abandoned as an explanation of the sun's heat and light, scientists have sought other theories that could fit the known facts. Lord Kelvin, the famous Scots physicist, suggested that the sun kept up its temperature by shrinking. The matter of the sun is constantly drawing inward upon itself under immense gravitational forces which reduce its diameter by about 250 feet per year. Squeezed at a pressure as high as a billion tons to the square inch, the sun transforms its gravitational energy into radiant energy that is emitted as light and heat. Compression of the sun's matter liberates energy in this way just as compression of the air warms up a bicycle tyre.

This compression effect probably accounts for some of the sun's energy, and was particularly important during the early years of the sun's existence. But it cannot possibly account for all the heat and light that have been radiated during the entire life of the sun. If the sun was formed from matter that was once widely dispersed in space contraction to its present size would provide enough energy to last twenty million years; and another twenty million years would see the sun shrivelled to the present size of the earth. These periods are mere instants in the lifetime of the sun.

Towards the end of the nineteenth century physicists began exploring inside the atom itself, and it soon became apparent that within the electrical merry-go-round of the atom there was a possible source of energy on an immense scale. The tiny particles inside the atom are held together by forces that are associated with energy far greater than those that hold one atom to another when molecules are formed.

Einstein proclaimed that in matter itself there is a source of energy; matter could be changed into energy. And calculations showed that this atomic energy would be liberated in prodigious quantities when matter was annihilated.

Some elements were found to undergo spontaneous atomic disruption as they changed into other elements. This discovery of radio-activity was followed by the suggestion that the sun's heat was maintained by radio-active elements in its interior. As the atoms of these elements disintegrated the energy released would raise the temperature of the sun and enable it to send out heat and light.

But once again calculation proved that this was not the way the sun obtained its energy supplies. A sun of solid uranium would yield only a third of the energy that it is known to radiate. Analysis of the sun's light spectrum shows no uranium lines at all, although this is the most plentiful of all radio-active elements on earth. This does

not necessarily preclude uranium from being on the sun; the metal may be hidden inside the interior. There is no doubt, however, that radio-activity can account for only a small amount of the sun's energy, if it is in fact responsible for any significant part of it at all.

There remained the possibility that the sun derived its energy from a large-scale disruption of matter into energy. The discovery of a preponderance of hydrogen, simplest of all atoms, on the sun lent support to this belief.

According to Einstein's formula, production of the radiation known to be released by the sun must involve the loss of more than four million tons of matter every second. So, in a year, the sun converts more than 130 million million tons of its matter into energy; this is the source of the sunshine that maintains life on our earth.

In spite of the scale of this self-destruction process, the sun is so enormous that it scarcely notices the loss. In the 2000 million years or so since the earth was formed the sun has lost only about one seven-thousandth of its total matter. It was for a time believed that the sun released its energy by the complete destruction of its matter. But this view is no longer held. The basic process is now thought to be the conversion of the sun's hydrogen into helium. It is the energy-liberating process that has been harnessed in the hydrogen bomb.

The atom of helium is slightly less in weight than four atoms of hydrogen. The transformation of four atoms of hydrogen into a helium atom leaves a little bit of matter over; this is released as energy. Every ounce of matter dispersed in this way releases enough energy to drive 10,000 family cars for a year.

In 1938 Hans A. Bethe, of Cornell University, worked out how this change from hydrogen to helium might operate in the sun and stars. The transformation takes place in six distinct stages, the net result being the disappearance of hydrogen and the production of helium. Energy is liberated in the form of gamma rays—these

being the highly penetrating radiations of much shorter wave-length than ultra-violet rays and X-rays.

The first stage in the sun's atomic energy process consists in the union of a hydrogen-atom nucleus with the nucleus of a carbon atom, forming nitrogen. The nitrogen nucleus then changes into a heavy carbon nucleus, which changes in succession into nitrogen, oxygen, nitrogen, and finally helium. During this last stage carbon is produced, replacing the carbon that was used at the beginning of the cycle. There is therefore no loss of carbon during the change; it acts merely as a ' carrier ' during the conversion of hydrogen to helium.

Altogether the cycle of change from hydrogen to helium takes about five to six million years. But all stages are taking place the whole time on the sun, and the radiation of energy is continuous.

Inside the sun atomic nuclei are moving at fantastic speeds. They collide with enough violence to bring about this cycle of transformations from one element into another. Here on earth temperatures of a million degrees are outside the range of normal experience. Hydrogen can be heated to transmutation temperature only with the help of atomic energy itself; that is why an ' ordinary ' atomic bomb is believed to act as the detonator in a hydrogen bomb.

The transformation of matter into energy at the rate of four million tons per second means that about 564 million tons of hydrogen are changing into 560 million tons of helium every second. But there is so much hydrogen on the sun that it could keep going at this rate for many thousands of millions of years. Since 1938, when the hydrogen-helium cycle was suggested as a feasible process for energy-production in the universe, scientists have been trying to confirm that it is in operation in the sun.

At one stage in the cycle atoms of 'heavy carbon' are formed. Only 1 per cent. of the carbon on earth consists of this carbon-13; if it could be proved that the sun's car-

bon contained a higher proportion of carbon-13 this would be direct support for the carbon-cycle theory. Analysis of the sun's light, however, has shown no carbon-13 at all. This means either that the carbon is buried away beneath the surface of the sun or that it does not take part in the helium-production cycle.

There is now evidence that conversion of hydrogen to helium on the sun takes place by a more direct route. The straightforward combination of one hydrogen nucleus with another produces an atom of deuterium, or ' heavy hydrogen,' the process taking about 8000 million years. Within four seconds of its formation this deuterium captures another hydrogen nucleus forming an atom of helium-3. Then, after 400,000 years, two of these helium-3 atoms fuse together yielding an atom of helium-4 together with two hydrogen nuclei and a burst of energy.

Calculations have proved that this route from hydrogen to helium would make more energy available than would the carbon cycle.

The energy produced during helium-formation is released as highly-penetrating gamma rays inside the sun. If our sunshine reached us in the form of gamma rays life as we know it would not be possible on earth. But the energy is transformed into rays of longer wave-length before being radiated from the sun, and most of it reaches us as heat and light. Radiations make such a tortuous journey from the inside of the sun towards the surface that they may take 10,000 years to get there. Most of them by that time have been converted to less dangerous rays; if any short waves remain they will tend to be absorbed by the sun's corona or by the gases of the earth's atmosphere.

As the sun continues with its job of energy-production the amount of helium will steadily increase. The effect of this will be to make the sun's temperature rise and energy will be liberated at an ever-increasing rate. In the future the sun will become hotter and more brilliant than it is to-day. Ten thousand million years from now the sun will

be sending out a hundred times as much heat and light, and its stocks of hydrogen will be running out.

When its atomic fuel has finally gone the sun will shrivel and its light will grow dim. Within a few hundred million years it will have disappeared entirely from view. But there will be no human beings on earth to watch with dismay as the sun's light dies. Life as we understand it will have been scorched from the earth in the intervening years.

5

Light gives the World Colour

As rays of sunlight reach the earth they are affected in one way or another by the things they meet. Some may be absorbed, their energy translated into heat or electricity or light of different wave-lengths; other rays may continue on their way if the substance that they meet is transparent; the rest will be reflected, bouncing from the surface to travel in a new direction until they reach the next obstacle in their path.

When we look at luminous bodies, such as the sun or stars, a fire or a lamp, the rays of light sent out by them in the direction of our eyes are absorbed by the sensitive cells of our retinas.[1] We see these objects directly in the light that they emit. But most of the things in our individual worlds are seen by courtesy of reflected light that has often been relayed from one surface to another until eventually it enters the pupils of our eyes. More often than not the composition of this reflected light has been affected by its experiences before it reaches our retinas. We see it, not as the so-called ' white ' light that reached the earth from the sun, but as light that stimulates the sensations we recognize as colour.

Until Sir Isaac Newton carried out his experiment with a prism colour was generally regarded as an inherent characteristic of any substance. A leaf was green because it sent out a special form of light that caused the sensation

[1] The retina is a light-sensitive layer at the back of the eye—see Chapter 11.

we recognize as green; the sky was blue because it emitted something that stimulated a blue sensation in our eyes. But Newton showed that ordinary sunlight was a mixture of rays of light, each capable of registering a different colour in our eyes. Sunlight passing through a prism is separated into its constituents, forming a pattern of coloured bands we call the spectrum. From red at one end of the band of coloured light the spectrum moves through orange, yellow, green, blue, indigo, and violet.

Nowadays we regard these different colours as representing light radiations of different wave-lengths. The undulations in the ether giving a 'red' sensation as they strike our eyes are about thirty-two millionths of an inch from crest to crest; those that we recognize as violet are about sixteen millionths of an inch in length. The intermediate colours have wave-lengths that diminish steadily between red and violet.

Light from the sun is a mixture of wave-lengths extending over the whole range of the visible spectrum. As it reaches our eyes it causes a complex mixture of sensations in the retina that we recognize as 'white' light. We think of sunlight itself as colourless, not because it cannot stimulate the colour cells of our retinas, but because it stimulates them all at the same time. To provide our eyes with an impression of a definite colour we have to isolate light radiations of the appropriate wave-length, removing others from the sunlight mixture. The isolated radiations can then stimulate the retina cells preferentially, and we perceive the light as a definite colour.

Our modern view of colour is radically different from the ancient theories which served until the time of Newton. We think of colour as the result of something being taken away from sunlight, not as a positive emanation from a coloured object.

When sunlight reaches the earth each object in its path absorbs and reflects the rays in its own characteristic manner. The reflected light is the light that eventually reaches

our eyes and enables us to 'see.' But substances vary in their ability to reflect rays of different wave-length. Some will absorb the short radiations at the violet end of the spectrum, reflecting the longer radiations which we recognize as yellow, orange, and red. The light that reaches our eyes from an object of this sort will therefore be light that is deficient in short-wave radiations; it will lack the violets and blues, and we shall receive an impression of orange or red. When we admire the beauty of a rich, red rose we are enjoying the radiations left over after the flower has absorbed the short-wave rays that it prefers. The colour of a cornflower, on the other hand, is caused by its reflection of the shorter rays at the blue end of the spectrum; longer-wave radiations have been absorbed.

If none of the radiations of visible light are absorbed, and all are reflected, the light that reaches our eyes is similar to that which reaches us direct from the sun. A highly polished metal surface reflects light in this way, forming an almost perfect mirror. When the surface of a good reflector is rough the light is reflected in all directions from the hills and hollows in the surface; the object then looks white, like a sheet of good-quality paper.

If, on the other hand, all the light radiations are absorbed, no matter what their wave-length may be, there are no rays left over to reflect into our eyes. A piece of charcoal, which can absorb all types of radiation in this way, appears black. It provides no stimulus at all to the sensitive cells in our eyes. Black is an absence of light.

Just as some substances will reflect certain wave-lengths of light and give the impression of colour, so others will transmit some wave-lengths and absorb the rest. When a glass of port wine is held up to the light its rich, ruby colour comes from radiations that are able to pass through the liquid without being absorbed.

The pattern of colour thrown on a church floor is built up from patches of light transmitted by the glass of the windows. Each pane has absorbed some rays from the

sunlight, allowing others to pass and to be reflected into our eyes from the flat stone floor.

This absorption of selected wave-lengths of light by different substances is responsible for most of the colour in our everyday lives. But some of the colours of nature are caused by separation of the mixture of waves in sunlight into a spectrum similar to that produced by a prism.

When light from the sun is travelling through the earth's atmosphere it is reflected and turned aside by particles of dust and moisture in the air. The rays with short wave-lengths, which give us a sensation of blue, are scattered more than the longer-wave, red rays. Light that would otherwise pass above the earth's surface is deflected in this way towards the earth; as we look skyward we see this light in the blue of the sky. But as we look towards the sun we see those rays which are reaching us direct; they have lost some of the blue rays by scattering and we see them as the red and orange rays of our sunset and sunrise.

In the same way light is scattered by small particles in the smoke from a cigarette. As it rises from the end of a cigarette the smoke appears blue; short-wave radiations of light are being scattered more than the longer ones. After it has been in the lungs cigarette smoke is grey; the moisture-coated particles are larger, and scatter the longer waves as well.

The fog lamp of a car is often fitted with a yellow glass; this absorbs the short blue waves which would otherwise be scattered by the droplets of moisture in the air. Less light is reflected into the driver's eyes.

A yellow 'filter' is fitted on a camera lens when landscape photographs are being taken on a hazy day; the glass absorbs much of the short-wave light that is scattered by particles of moisture in the air. The picture is therefore clearer.

This scattering of light by floating particles in the air is caused by reflection of the light waves from the particle surface. It is the size of the particle that decides which

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wave-lengths of light will be affected most. If the particle is extremely small by comparison with the wave-length the undulations sweep past it like a sea wave flowing around a tiny rock. Only when the rock is large enough will it turn aside the waves.

In the atmosphere the molecules of gas forming the air itself are small by comparison with the smallest waves of visible light. But even so there are so many of them that they could account for the blue of the sky without any help from dust or floating moisture droplets.

The colour of the sea, which varies from a cold, dull grey through green to the most vivid blue, is to some extent controlled by floating particles in the water. Shallow water near the beach is coloured green from a combination of scattered light and light reflected from the sea bed. Floating particles in the water turn aside the shorter waves of the light, sending 'blue' light back towards our eyes. But in shallow water the sand on the sea bed is reflecting yellow light, so that our eyes receive a mixture of yellow and blue. We register this as green.

Nature uses this scattering of light to provide some of the colours in living things. The white in a butterfly's wings and in the petals of a flower are caused by small air bubbles that reflect the waves of light in all directions. The opaque whiteness of a flower will disappear if the petals are squashed, forcing out the bubbles. Whiteness of this sort is also produced by the foam that caps breakers in the sea.

Some animals use particles so small that blue light is deflected more readily than the light of longer waves. The bright blue patches beneath a dragonfly's wings are formed in this way.

When light passes through a prism its constituent rays are turned aside to different degrees, so that they are separated to form the spectrum. If we look at the prism in such a way that the light falls on to our eyes the colour sensation we receive depends on the position of our eyes

in the spectrum band. In one position we see only red light coming from the prism; in another position we see blue or green or yellow. Nature uses this principle to bend light in a similar way through different degrees depending on its wave-length, so providing some of the most beautiful colours that we see in the world around us. The rainbow is a spectrum formed from sunlight split into its constituent colours as it passes through raindrops in the air.

Light shining on the bevelled edges of a mirror or on a gem-stone or the ridges in a cut-glass vase will separate into its coloured rays as though it had been shining through a prism.

The actual colour-detecting processes that take place in the eye are little understood. It is believed that there may be three distinct types of receptor cell in the retina, each being influenced preferentially by different wave-lengths of light. Light from the red end of the spectrum affects one type of receptor cell, and light from the violet end another. Green light affects the third, but stimulates the other two as well.

The effect of other wave-lengths is to stimulate these receptor cells to different degrees. Yellow light, for example, will tend to stimulate the red and green receptors, and the blue one only slightly. Blue light favours the green and violet cells.

This apparent reliance on three ' primary '-colour receivers for our colour sensations has made the detection and appreciation of colour a complex undertaking. If we had a separate receiver in the eye for every narrow ' colour band ' in the spectrum each colour could operate its own receiver and the brain would detect each ' colour ' as a distinctive stimulus. But the use of three types of receptor-cell, all stimulated to some extent by most wave-lengths, means that the brain detects colour in the form of different balances in the intensity of stimuli in the three types of cell. We therefore detect mixtures of light radiations of widely differing wave-lengths as the same ' colour.'

'White,' for example, is the sensation produced by the normal mixture of rays reaching us in ordinary sunshine. But the three types of receptor cell can be stimulated in similar proportions by combining various pairs of different wave-lengths. The colours represented by these wave-lengths are called complementary colours. Together they produce the sensation of white; when one is taken away from white light the other is left. Crimson and green, orange and blue, primrose and violet are complementary colours.

There is therefore an important difference between the sensation of colour registered by the eye, and the colour we associate with each individual wave band of the spectrum. A compound of sodium heated in a flame will emit a typical yellow light; ordinary salt will throw out this ghostly yellow from a coal fire. The yellow of the sodium flame consists of light of a distinct wave-length in the yellow region of the spectrum; it is like sunlight from which everything but yellow light has been removed.

Yet we can also make a yellow light by removing only blue from sunlight. The remaining mixture of rays stimulates the eye in the same way that the 'pure' yellow does. 'Colour' applied to the distinct rays forming part of the spectrum is not the same as 'colour' as registered by the eye. This double meaning in our description of colour explains apparent contradictions we meet in colour mixtures. If blue and yellow pigments are mixed on a painter's palette the result is a green. Yet if two lanterns shine separately on a white screen, one through a blue glass and the other through yellow, the two colours together form white.

Blue pigment used by the painter is absorbing all the colours from white light except for blue and green; this is reflected and reaches our eyes. The yellow pigment is absorbing violet and blue from the white light and reflecting yellow and green. The two pigments together absorb red, yellow, blue, and violet, so that only green is left. This is reflected and reaches the eye.

The two lanterns, on the other hand, are throwing a mixture of two complementary colours on the screen each of which is reflected into the eyes, producing white.

When pigments and dyes are used for giving colour to paints and textiles and other manufactured goods they do so by absorbing certain wave-lengths of the light that falls upon them and reflecting others. Two dyes will often give identical colour sensations in daylight by reflecting different mixtures of light; a dress made up from fabrics using two such colours will be satisfactory so long as the two are seen in daylight. But artificial light does not emit the same range of wave-lengths as we get in the sunshine spectrum; an electric bulb, for example, is lacking in short radiations forming the blue of the daylight spectrum. It has a yellow appearance to the eye.

If one of the matching colours used in the two dress fabrics depends on reflection of blue light, and the other does not, the shades will differ when seen in artificial light. This lack of blue in artificial light makes dark blue clothes look black. Blue cloth absorbs all but the blue rays from daylight; in artificial light there are no blue rays to reflect, so that the cloth absorbs all the light that falls upon it. It is black.

So the colour of anything we see depends not only upon the nature of the substance itself, but upon the light that is falling on it. Colour is determined by the light rays that reach the eye; these are rays that were present in the light to begin with, and which have survived their meetings with substances in their path.

Even when a colour has been identified accurately by a knowledge of the light waves that are causing it we still cannot be certain that it will produce a definite shade in the eye and brain of the person seeing it. The sensation of colour is not a fixed and rigid thing; it depends upon the health and condition of all the human tissues that are involved in its perception.

The receptor cells which detect the light that reaches

the eye are easily tired; if we stare too fixedly at a patch of colour on a printed page the retina cells responding to this colour will tend to become fatigued. If we then transfer our gaze to a blank white wall we can ' see ' the outline of the coloured figure. But we see it in its complementary colour.

By staring at a blue disc in this way, for example, we tire the blue and green receptor cells in the retina. When we look at the white wall our eyes are receiving a composite mixture of rays that stimulate all three types of receptor cell. But the blue and green cells that have been detecting the light from the blue circle are fatigued; they are stimulated less than the red receptor. We therefore see an orange-yellow image on the white wall. In the same way we see green streaks after looking at the sun.

If human beings stared persistently at the things they see this phenomenon of colour-cell fatigue would confuse our colour sense and complicate the sensations that we send off to the brain. But our eyes are never still; they move about from one point to another as though examining different sections of the scene in turn. The colour-receptors of the retina have no time to become fatigued by concentrating on one patch of colour for too long. Indeed, we find that a considerable physical effort is needed to stare intently at a single point for as little as five seconds without shifting the gaze to something else. This is the eye's way of protecting itself from too much colour fatigue.

Even so the effect of colour fatigue is of extreme importance in the design of textile patterns and in painting, where one colour lies close alongside another. As the eye moves from one patch of colour to another it superimposes a shade caused by fatigue in the colour cells that have been in use. A patch of yellow surrounded by a broad band of black will always look much lighter than the same yellow with a white surround. As the eye moves from the black surround to perceive the yellow its colour cells are fresh; nothing has been reflected to them from the black.

But when the eye moves towards the yellow from a white surround its colour cells have all been working and are tired. They cannot respond to the yellow so vigorously as they do when moving to it from an area of black. The yellow therefore looks much darker in its white surround, even though it is constitutionally the same.

Similarly a pattern in which yellow is surrounded by a red tends to carry a greenish after-image on to the yellow. The latter has a greenish tinge. If the yellow is surrounded by a green it has a reddish after-image carried to it, so that the yellow seems warmer than that which was surrounded by the red.

These effects, caused by tiredness that afflicts the colour cells of the retina, must be taken into account by artists and designers if the colours they use are to create the impression intended on the human eye. But there are other influences as well which can alter the ' colour ' of a colour as it is perceived in the visual centre of the brain. This is an ' addition ' effect that is noticeable particularly when designs are more intricate and colours are picked up in rapid succession by the sensitive cells of the retina. In this case one colour is carried over on to another by the rapid movement of the eye. Small patches of yellow forming a dotted line on a background of green will tend to look much greener than the yellow does by itself. As the eye sweeps down the line of yellow patches it carries with it an impression of green from the spaces in between.

If the yellow dots are placed on a reddish background they will have a redder shade caused by a carry-over of red as the eye moves from one dot to the next.

These two effects caused by the close proximity of colours will often come into play at the same time in a colourful and intricate painting or design. Experience and understanding of them enables an accomplished artist to enhance the beauty of his work. Ignorance of the effect of one colour on another can be disastrous.

The more we discover about this strange phenomenon

of colour, the more involved does it become. In the purely scientific sense we can assess the relative amounts of radiations of different wave-lengths that are reaching the eye; we can label the mixture with a definite colour, in that we know the sort of response this light-mixture will stimulate in an average human eye. The nature of the light is controlled by the characteristics of the substance from which it is being emitted or reflected; it is influenced by its experiences on its way to the eye. But even when its final composition is accurately known this light-mixture represents a ' colour ' only by permission of the human eye and brain. Colour is a sensation that can vary greatly from one individual to another, and from one set of circumstances to another.

It is this flexibility that enables colour to contribute so much to the beauty of our everyday lives.

6

Living Light

THE lamps that we use to lighten the darkness of night are friendly, inanimate things. The candle flame flickering in a sudden draught; the glow from an electric bulb; or the light from the sun or the moon: all these are familiar and understandable. But light from a living plant or animal body is something to set our flesh acreep. This is the light of ghosts and dancing goblins, the light of decaying corpses and eerie places, the light that glows in the windows of haunted granges or flits and flickers in the depth of a wood.

Yet there is nothing mysterious about the light we associate with life. The light of a glow-worm is a natural accompaniment to the chemical processes of its body; the ghostly glow of a decaying tree is merely a release of energy by fungi that are feeding on the rotting wood.

Whenever a chemical change takes place there is a change in the balance of energy too. Often energy is emitted as heat; sometimes it is released as light. In many of the everyday chemical reactions that go on around us heat and light are released together, as in a coal fire.

In the living body innumerable chemical changes are for ever taking place. Most of the energy set free is in the form of heat, and there are complex mechanisms in human beings and other warm-blooded creatures for controlling the heat balance of the body. But some creatures, for reasons that are often obscure, have learned to carry out chemical changes in the body which release energy as

light. These are the creatures that glitter and glow in the darkness of earth and sea.

The emission of living light is a comparatively common phenomenon. There are light-producers in some forty different animal orders and in at least two types of plant. Light is generated by insects, bacteria, fungi, fishes, protozoa, squids, and all manner of creatures in the sea. Even man is believed to emit a faint luminescence from his tissues.

The sea is aglow at all levels with myriads of twinkling lights. On the surface one-celled protozoa and other small creatures emit pin-points of light that coalesce into carpets of luminescence. Whenever the water beside them is disturbed these floating animals of the plankton protest by lighting their internal lamps, like drowsy clubmen reddening with fury as they are awakened from an afternoon's nap.

In the depths of the sea living light comes into its own. Here, in a world of perpetual night, the blackness is pierced by lights from the creatures that make it their home. Goggle-eyed fishes pattern their bodies with patches of light or dangle their lamps on a built-in fishing rod to act as a lure that attracts their prey. Some deep-sea fishes have lights at the back of their eyes, forming headlamps that probe the darkness ahead.

Luminescent sharks feed on the sea-bed with the help of light from their glowing bellies. Prawns and squids throw luminous clouds into the water or cover their bodies with a glowing slime, forming undersea ghosts to scare their attackers.

In the darkness of the sea living light serves its owners in many practical ways. The pattern of light on the body of a fish is an identification mark. It helps the male fish to recognize his mate, making breeding possible in the stygian darkness of the deep sea. Lights carried by fishes can attract prey, and scare predators.

Yet there are many creatures of the sea which produce

light for no clear reason at all. Clams and worms will often glow brilliantly, though their lives are lived in burrows scooped from the ocean floor. What can be the purpose of lights that are seen only by the creature that carries them? Many of the simple animals that anchor themselves to the sea-bed are luminous; sponges and jellyfish carry lamps, though it is difficult to see how light can serve creatures that are immobile or drift helpless in the ocean currents.

The light of the 'flaming sea,' which is lit when the surface is disturbed, is an automatic reaction on the part of the tiny, floating animals. Noctiluca, a simple one-celled animal less than a twenty-fifth of an inch in diameter, lights a lamp so small that it cannot easily be seen on its own. But so many of these protozoa float in the sea that they can mark out the wake of a ship with broad luminous bands which are visible for miles.

In the more complex bodies of fishes the luminous lamps are apparently under more direct nervous control. The light can be switched on and off at will, and arrangements are made for using them to best advantage. The glands that produce the living light are equipped with lenses to concentrate the beam; they have colour filters and diaphragms and are backed by a layer of reflector-cells that throw the light forward. Some fishes can rotate their light glands, rolling them inward to turn the light off; others have shutters that cover the lens.

On land, living light is often less noticeable than it is in the sea. Yet many insects use self-generated light, sometimes to attract their mates, often for no apparent reason at all. Fireflies and glow-worms are well known in many parts of the world, where they light up the darkness with little flashes from the lamps on their bodies. The light from the female is usually more intense than from the male. A female glow-worm enclosed in a perforated, opaque box does not attract a male; yet in a transparent cage the lights emitted by the female will bring males crowding to the cage. Some moths emit flashes of light as they fly through

the air, and beetles will prance and posture to display the luminous patches on their bellies to their admiring mates.

On the land, as at sea, there are creatures that glow as part of the involuntary routine of life. Grubs in the soil throw a diffused light from their bodies that is seen only by themselves. Some beetles emit a glow that comes from the eggs they are carrying. The luminescence of decaying wood is caused by fungi that glow as a matter of course; their lamps never go out. Bacteria feeding on decaying flesh emit a continuous light that we associate with death and putrescence.

The light emitted by fireflies is noticeable in the dark ness but the amount of light generated is extremely small. Measured with the help of delicate modern instruments, the firefly's flash is a light of about six-thousandths of a lumen; the brightest firefly of hundreds tested emitted nine-thousandths of a lumen. Between 1000 and 2000 fireflies would, at this rate, generate as much light as a candle. Nearly 140,000 insects would have to work together to provide the light given by a 60-watt bulb.

In spite of the low intensity of the firefly's light, the efficiency of light-production is high. The light is liberated with only an infinitesimal amount of heat as well. Compared with a candle, the firefly is very much superior in this respect; a candle wastes 80,000 times as much of its available energy as heat. The insect converts about 98 per cent. of the energy it uses into light.

This production of 'cold' light by animals is an achievement that we cannot yet match in our human world. Our common sources of light are comparatively inefficient, much of the energy being wasted as heat. If we could find a way of converting chemical energy almost completely into light, as the firefly does, we could illuminate our lives very much more economically than we do now.

Scientists have studied the processes used by living things to produce light. They have found that throughout the plant and animal worlds the technique remains

basically the same. It has been developed independently, along almost identical lines, by different species of living things.

In 1886 the light-producing substance used in nature was first extracted from luminescent clams. This natural chemical, given the name luciferin, is oxidized in special glands of the animal body, just as other substances are oxidized during the ordinary chemical processes of life. But instead of liberating energy as heat luciferin emits light. This is the light that gives bacteria and fungi their continuous glow, and flashes from the windows in the firefly's thorax.

Like other living processes, the oxidation of luciferin is controlled by a supervisory chemical, an enzyme, called luciferase. Both luciferin and luciferase can be extracted from the glands of luminous animals. Mixed with luciferase in a test-tube and provided with a supply of oxygen, luciferin will glow as it undergoes its oxidation and liberates energy in the form of light.

In bacteria and fungi, luciferin is manufactured continually to replace the material lost by steady oxidation. But in animals that can turn their lights off and on the oxidation of luciferin is controlled by the nervous system. Like any other chemical reaction, it can be stopped by withholding supplies of one or other of the chemicals involved. Luciferin will not emit its light unless it receives an adequate supply of oxygen or of luciferase. And it is by controlling the flow of one or other of these substances to the light glands that the animal can switch its lamps off and on at will. Substances such as DDT or spider venom, which affect the nervous system, will stimulate light-production in a luminous animal.

Usually animals that enjoy producing light will do so with the help of special glands in which the luciferin reaction can take place. But some fishes prefer to let bacteria generate the light they need, providing special pockets in the body in which the colonies of bacteria can

live. Food chemicals and oxygen are supplied to the bacterial colonies which, in return, provide the fish with light. Sometimes animals are invaded by less welcome light-producing bacteria which cause disease. Shrimps and fleas will often die a luminescent death.

The chemical structures of luciferin and luciferase are still unknown, and the light-generating process cannot yet be duplicated synthetically. Many other natural products, such as tea and coffee, will emit light as they oxidize slowly in the air. The phenomenon of natural luminosity is more common than was once supposed, and in due course it will no doubt yield its secrets to the chemist.

Already synthetic chemicals have been made which liberate 'cold light' when they oxidize. Some of them were used as markers in sea-rescue equipment during World War II. The oxidation that produces light can operate only when the chemicals are wet.

Luciferin, similarly, will emit its light only in the presence of water. Luciferin and luciferase have been kept for twenty-six years by drying the bodies of light-producing animals. At the end of that time the natural chemicals were still able to oxidize and liberate light.

A careful study of 'cold light' has shown that there is nothing unusual about it other than its source. The light corresponds to rays in various regions of the visible spectrum and is tinted with the corresponding colour. Some animals prefer a rosy light, others yellow, green, or blue. There are neither ultra-violet nor infra-red radiations in the living light.

At present we human beings have found no way of putting nature's lighting system to practical use. But other more ingenious creatures have; the weaver bird, in India, uses fireflies to light the inside of its nest.

This generation of light by living things is described as luminescence because it takes place without the accompaniment of large amounts of heat. The light liberated is energy set free during chemical reaction between luciferin

and the oxygen of the air. But luminescence is not confined to living things; it is a phenomenon that has been recognized for centuries in certain types of mineral.

Nearly a thousand years ago the Emperor of China was intrigued by the strange behaviour of roasted oyster shells. Mixed with other substances, they appeared to absorb light during the day and emit it with a ghostly glow at night.

During the Middle Ages the alchemists made great play with this peculiar property of certain minerals. Vincentius Casciarolus, an Italian bootmaker with an interest in alchemy, became famous for his discovery of the Bologna stone. This stone, made by burning the mineral barytes, emitted an orange light in the dark. We now know that the luminous material of the stone was barium sulphide.

During the eighteenth century other luminous materials were discovered, and the phenomenon of light-emission became a familiar one. It has become of tremendous practical importance in our modern, electronic world.

Many luminescent substances are now being made commercially on a large scale. They can be stimulated by all sorts of radiation in addition to visible light, absorbing energy from ultra-violet rays and X-rays, cathode rays and gamma rays. After stimulation in this way these substances respond by emitting light. They are now described in general terms as phosphors.

Some phosphors will send out their light immediately as light or other radiations stimulate them. Then when the stimulation stops the light-emission stops too. An immediate reaction of this type is called fluorescence. Other substances will store up the energy that stimulates them and go on emitting light for hours or even days after stimulation has stopped. This is the phenomenon we call phosphorescence.

Fluorescent materials are used for coating X-ray screens; when the X-rays strike them light is emitted with an intensity that depends upon the strength of the stimulation.

X-rays that have passed through the human body will cause a pattern of fluorescence that gives a picture corresponding to the selective absorption of the X-rays in bones and other organs.

A layer of phosphor on the inside of a television tube will fluoresce as it is stimulated by the moving beam of cathode rays. The picture on the tube consists of countless tiny spots of glowing phosphor, each spot giving out light with an intensity that matches the intensity of light at a corresponding point in the scene before the camera.

The luminous dials of instruments and watches are painted with a mixture containing a phosphor and a radio-active substance. Rays from the radio-active mineral maintain the phosphor in a state of continuous stimulation; it responds by sending out light.

Fluorescent dyes are used in the brilliant poster paints that seem to glow in daylight; stimulated by the sunshine, these colours send out an extra ration of light. Colourless, fluorescent 'dyes' are added to detergents; clinging to the fibres of our clothes, they emit a blue light that tends to counteract the creamy colour of the natural fibres. They really do make clothes look 'whiter than white.'

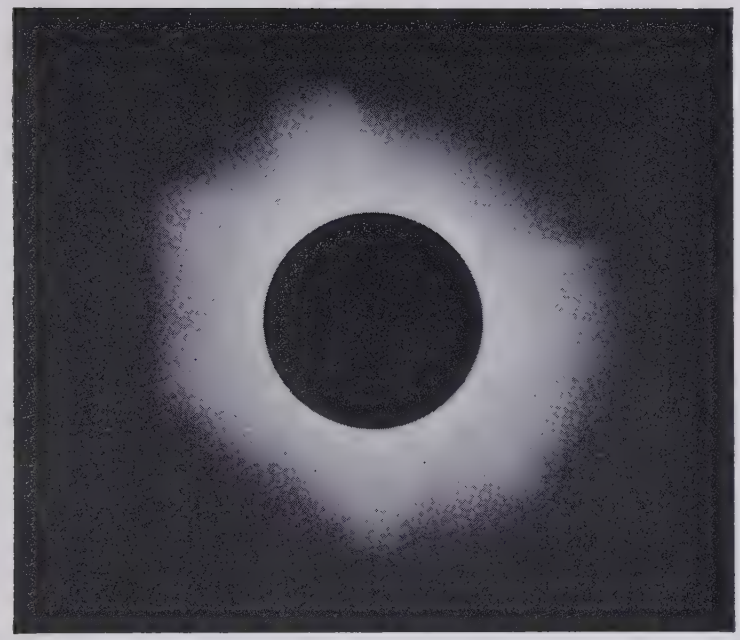


Photo Swarthmore Eclipse Expedition

THE CORONA

The sun's corona, photographed during the total eclipse of January 14, 1926.

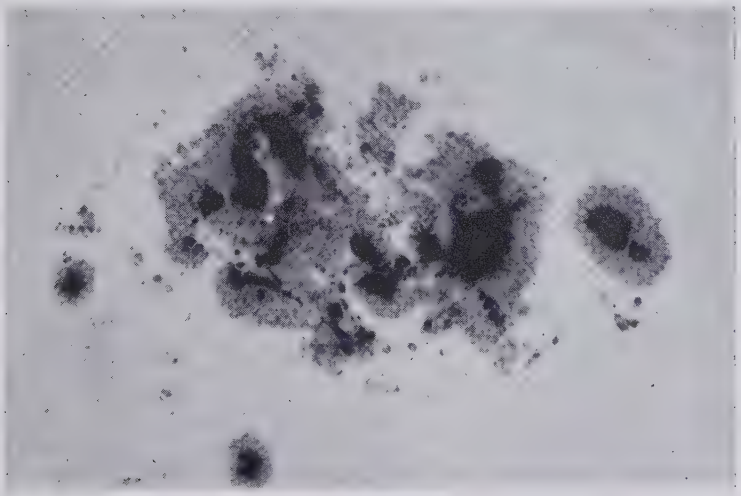


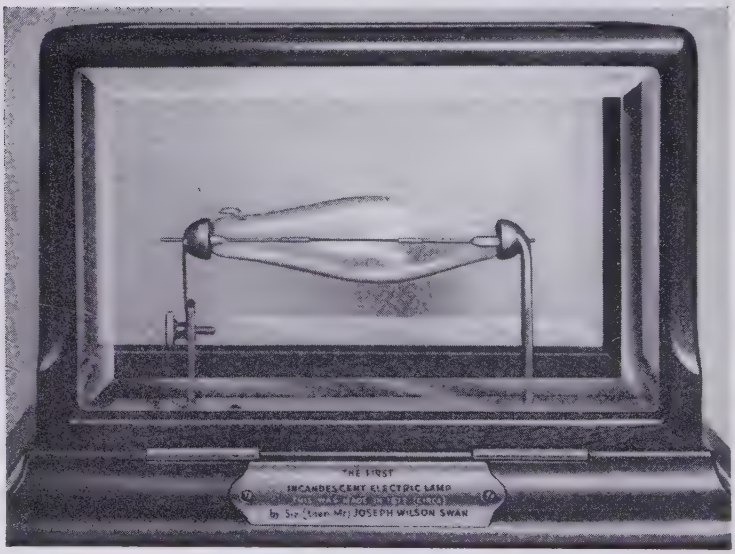
Photo Mount Wilson and Palomar Observatories

SUNSPOTS

This photograph was made on May 17, 1951.

LAMPS

In these primitive stone lamps animal fat was burned with the help of crude wicks



Photos E. L. M. A. Lighting Service Bureau

The first incandescent lamp, made by Joseph Wilson Swan in 1877

7

Light made by Man

In ancient times the coming of night was awaited with dread by primitive man. As darkness came over the land he retired to his cave, protecting himself from beasts that prowled in the night. Without light, man lived in a world hemmed by shadows. Darkness and death went hand in hand.

The discovery of fire was the first step towards man's conquest of night. Fire gave man heat for cooking his food and making his simple metal tools and weapons. But the flames of his fire also gave him light. Man no longer depended entirely upon the sun; fire-light extended the length of his active day.

This dim light thrown out by smouldering wood is a far cry from the brilliant light we expect from our lamps to-day. Yet most of our modern gas and electric lamps differ little in principle from the cave fires of primitive man.

To make artificial light we heat solid substances until they are hot enough to send out visible radiations. As the temperature rises the waves grow shorter until they reach about thirty-two millionths of an inch in length; they enter the range of visible light. A heated poker then becomes red-hot, sending out the long-wave red rays as it starts to become luminous. Gradually as the temperature rises the rays get shorter and move through the visible light spectrum towards the violet end. The light from the heated solid becomes steadily whiter as the temperature increases.

But producing light by heating a substance until it glows is an inefficient business. It is like a piano on which a high note can be reached only by pressing all the keys below it as well. We cannot have the note we want all by itself; we have to accept the lot or nothing at all.

As the waves grow shorter when a solid is heated, they do not replace the longer waves; they are added to them, so that the incandescent substance is sending out a range of waves in which visible light forms only a modest fraction of the whole. Most of the energy poured into the heated solid is lost as longer rays of radiant heat.

When wood or coal or other combustible materials are burning in a fire heat is released as a result of the chemical changes taking place. The fuels we commonly use are all organic compounds; they contain carbon in association with hydrogen and other elements. When these fuels burn, the carbon and hydrogen in them combine with oxygen of the air, forming carbon dioxide and water respectively. Heat is released in the process.

In an ordinary fire there is not sufficient oxygen available to combine with all the wood or coal; air cannot get into the base of the fire quickly enough. Particles of unburnt carbon and partly decomposed fuel float away in the flames. These solid particles are heated by the energy released in the fire and become incandescent, sending out light. This is the source of light in a fire.

As primitive man cooked his meat he would notice how fat dripping on to the fire burst into yellow flames. It was an obvious step for him to collect the fat deliberately in a hollow stone dish or earthenware bowl and use it as a source of light. The earliest lamps were bowls of animal fat or oil in which a piece of floating wood or fibre acted as a wick.

Simple lamps of this sort, made from a hollowed-out stone, have been found in Stone Age settlements. Sea shells were often used, a simple fibre wick resting in the natural channel provided by the shell. Sea-shell lamps were light-

ing human dwellings in Mesopotamia more than 4000 years ago.

Over the years this simple oil-lamp was modified and improved. The floating wick gave way to a fibre wick fixed to the vessel. The oil was enclosed, leaving only a small opening through which the wick appeared. Gadgets were introduced for raising and lowering the wick, and the lamp design was improved to allow more air to get at the burning oil. But in spite of all the improvements, the oil-lamp we know to-day is essentially the same as that which was burning at Ur of the Chaldees at least 2500 B.C. Millions of people all over the world still rely on the oil-lamp to provide them with light.

Until a century ago oil for the world's lamps came from animals and plants. Fishes and other sea creatures rich in oil were hunted as fuel; whales were speared off the coast of Europe to provide seafaring nations with lamp-oil; American Indians burned fats that they squeezed from salmon. In the Shetland Isles wicks were threaded through the bodies of sea-birds; oil from the birds burned on the end of the wick protruding from the beak. In Scandinavia the Great Auk, now extinct, was used as a lamp with a wick inserted in its body.

Wherever men lived Nature provided some sort of oil that would burn in these simple lamps. In cold mountainous districts torches were made from resinous pines; in the tropical islands of the Pacific the coconut served as a source of oil.

Often these animal and vegetable oils were in short supply. Oils that would burn could be eaten as well. And food took precedence over light. But the middle of the nineteenth century saw the tapping of the earth's vast resources of mineral oil. Paraffin distilled from petroleum took over the task of lighting the lamps of the world. In 1853 mineral oil deposits were discovered in Austria and served as a light-source for Europe. Six years later the

Pennsylvania oil-fields were opened and there was oil aplenty for the world.

Though much of the fatty material of animals and plants is liquid, there is also a lot of solid fat as well. This fat, in the form of tallow, has been used as a light fuel for thousands of years; it was made into candles. The earliest candles were little more than bundles of fibre dipped into molten tallow. The rushlight was a cheap and simple candle that we associate with Elizabethan times. It was made by peeling rushes, leaving only enough skin to support the pithy interior; the peeled rushes were then dipped into molten tallow which was allowed to harden. A rushlight two feet long would burn for an hour or more at a cost of only about a twentieth of a penny.

The candle proper was a much more elegant and expensive affair. Candles were made by dipping a fibre wick into molten tallow time and time again, each successive layer being allowed to harden. Candle-making was a highly respected craft, and its secrets and standards were jealously guarded during the Middle Ages. Like the oil lamp, the candle has stayed with us to the present day in spite of all the more ingenious forms of lighting we enjoy. The modern candle is manufactured on automatic machines and is as much a masterpiece of precision engineering as the electric lamp bulb. In Elizabethan days servants were employed as candle-snuffers; they made a tour of all the burning candles at half-hour intervals, snipping off the wick that was left smouldering when the tallow burned away. Nowadays our candles are so designed that wick and tallow can cope adequately with each other. The wick is woven so that it bends as the candle burns; the end of the wick is burnt away in the hot, outer part of the flame.

Although the fuel of the oil lamp is a liquid and the tallow of the candle is a solid the flame in each case is a region of burning gas. Oil is vaporized as it rises up the wick, and the gas burns in the oxygen of the air. The inside

of the flame is comparatively cool and consists of vaporized oil or fat; the outer part of the flame is hot, where chemical reaction is taking place with the atmospheric oxygen. As in an ordinary fire, it is the particles of unburnt carbon and other substances that provide the light. If a candle burned more efficiently it would not be so good a source of light.

By the end of the eighteenth century the Industrial Revolution was well under way. Coal was becoming of supreme importance as a fuel, and its stored-up energy was driving the factories and mills.

Coal itself could not easily serve as a fuel for lamps. But it was discovered that coal heated in closed retorts provided an inflammable gas. This gas would burn in air with a luminous flame and could therefore be used as a source of light. Early experiments with coal-gas were carried out by William Murdoch, an engineer employed by the famous Birmingham firm of Boulton and Watt. Towards the end of the eighteenth century Murdoch was living at Redruth, Cornwall, superintending the installation of one of Watt's pumping engines. He became interested in coal-gas, and in 1792 installed gas lighting in his cottage.

When Murdoch returned to Birmingham in 1799 he carried on with his experiments and improved the methods of making and purifying coal-gas. In 1802 he had progressed so far that he was able to light the outside of the Boulton and Watt factory in Soho, Birmingham. A year later he had installed gas lighting inside the building too. During the same year the Lyceum Theatre in London was lit by gas. In 1806 Murdock fitted gas lighting into the cotton mill of Messrs Phillips and Lee. By 1809 gas lamps were shining in Pall Mall. Soon the flickering gas flame was casting its baleful light in homes and factories throughout Britain, and coal-gas manufacture became an important industry.

The light from these early gas installations was poor

and uncertain by present-day standards. Light came, as in the candle and oil flames, from the particles of unburnt carbon that were heated to incandescence. These particles remained unburnt only because there was insufficient air getting to the gas flame; given an adequate supply of air, the carbon in the coal-gas mixture would burn away completely, forming carbon dioxide. The gas flame was luminous only because the gas was incompletely burned.

In 1855 the German chemist Bunsen invented the gas burner that is still used in every chemical laboratory. In the Bunsen burner air is allowed to mix with the gas before it reaches the flame. The carbon and hydrogen in the coal-gas are able to burn away more completely, so that more of the energy locked up in the chemicals of the coal-gas is released. The flame of a Bunsen burner is hotter than the flame of gas burning quietly at the end of a gas pipe. The particles of carbon are burned away, so that the flame is no longer luminous. There are no incandescent solid particles to emit light as there are in the ordinary gas flame.

Although Bunsen's invention allowed gas to be burned more efficiently, the hot flame of his burner was useless as a source of light. But thirty to forty years later Otto von Welsbach showed how the Bunsen flame could be made to provide a light far more effective than that from the simple luminous gas flame.

Von Welsbach invented the gas mantle. This was a hood of cotton fabric impregnated with a mixture of special minerals, thoria and ceria. When the mantle was fitted over a hot gas flame the cotton burned away, leaving a flimsy web of these minerals. Raised to a high temperature by the gas flame, the minerals became incandescent and threw out a steady light.

The mantle stimulated the development of gas lighting and of oil lighting too. It allowed more of the energy locked up in these fuels to appear as light. And apart from

comparatively minor modifications, the technique of using a mantle to release light from burning fuels has remained unchanged to the present day.

Meanwhile, as gas was bringing 'piped' light for the first time into Victorian homes, a new form of artificial light was on its way. In 1810 Sir Humphrey Davy showed how electricity could jump across the gap between two carbon rods, forming a continuous spark or 'arc' that emitted light. But Michael Faraday had not, at that time, developed the dynamo and there was no suitable way of generating a continuous current of electricity. The dynamo came during the 1830's, ushering in the age of electricity by providing a source of continuous current. With the dynamo, electric light became a practical proposition. In 1846 electric arcs were lighting the Paris Opera House. Soon these brilliant lights were being used for lighting many important buildings and streets. The Thames Embankment was lit by arcs, and so were parts of the City of London.

The modern arc light still makes use of the electric spark as its source of light. But the enormous expansion of electric lighting during the last century has been made possible by the invention of the filament lamp.

When electricity flows through a metal wire it has to overcome the resistance offered by the metal to its passage. Electrical energy is translated into heat, and the temperature of the wire rises. If the resistance is great enough the wire becomes so hot that it emits visible radiations; the wire glows and is a source of light.

Simple electric lights of this sort were made more than a century ago. In 1840 Grove devised a filament lamp that was little more than a fine platinum wire inside an inverted tumbler standing in water. A current of electricity made the platinum wire glow. Although the filament lamp was so simple in principle, it was many years before it could be brought into general use. The filaments had to be drawn very fine and with great accuracy. They had to be uniform

in thickness if they were to throw out their light satisfactorily.

Also the filaments had to be made in such a way that they did not burn away in the air. Grove used platinum in his simple lamp, because this metal does not react with the oxygen in the air when it is heated to incandesence. But platinum is a rare and costly metal and could not be considered as a commercial proposition. Most common metals which could be used as filaments are rapidly destroyed when heated in the presence of air. The non-metal carbon, which also conducts electricity, will burn instantaneously when heated in the air; it unites with oxygen to form carbon dioxide gas.

Five years after Grove had made his platinum filament lamp an American inventor, Starr, of Cincinati, made an electric filament lamp that overcame this difficulty. He enclosed the carbon filament in a thin glass bulb and then pumped the air from the bulb. When electricity was passed through the filament the carbon glowed, and, in the absence of oxygen, it did not burn away.

By 1878 Joseph Swan had brought the carbon filament lamp into commercial use. Working independently Edison developed a similar lamp in the United States in the following year. These lamps made possible the tremendous growth of the electrical industry at the end of the nineteenth century. And as more and more generators came into action they, in their turn, stimulated a demand for more efficient lamps. By 1882 many well-known buildings were lit by filament lamps. Filament bulbs for domestic lighting were introduced in 1889.

The carbon-filament bulb had many practical disadvantages. The filaments were delicate and short-lived. They could not be heated too strongly, as the carbon tended to evaporate and cover the inside of the bulb with a dark film that intercepted much of the light. Yet to make the filament give more light it had to be heated to as high a temperature as possible. Towards the end of the nine-

teenth century great efforts were made to find strong filaments that could be heated to higher and higher temperatures.

Otto von Welsbach, recognizing that the electric lamp was going to oust his gas mantle in domestic lighting, turned his attention to the filament bulb. In 1897 he brought out the osmium filament lamp.

In 1909, after an immense research effort, a method was devised for drawing tungsten into wires with the help of diamond dies. Since then tungsten-filament lamps have come into almost universal use.

Nowadays electric lamp bulbs are being made in huge automatic machines which turn out 100,000 or more in a day. The filaments, coiled from wire little more than half the thickness of a human hair, are drawn so accurately that they do not vary in thickness by more than a fortieth of the diameter of the wire.

These coiled-coil filaments of tungsten are raised to temperatures of 2500°C. They send out about seven times the light per unit of electricity that the carbon filament did. And they will continue to do this for, on average, 1000 hours or more.

Despite this amazing progress in the application of electricity to light-production, we still have little to be proud of from the point of view of sheer efficiency. The modern gas-filled bulb delivers only a fraction of 1 per cent. of its electricity in the form of light. Most of the electricity is transformed into heat.

In recent years a new lamp has appeared which gives us a bigger return of light for every unit of electricity used. This type of lamp, the discharge lamp, is a descendant of the arc lamp that was providing artificial light before the filament bulb came into use. It is now growing steadily in importance.

An English scientist, Hawksbee, carried out an experiment before the Royal Society in 1710; electricity was allowed to flow through a tube from which most of the

air had been removed. As the current flowed the tube glowed with a strange, spectral light.

Almost two centuries were to pass before this method of producing light was adapted to everyday use. It is the basis of our modern discharge lamps. The first experimental discharge lamps were developed in 1895. They contained carbon dioxide gas at low pressures, emitting a 'daylight' glow when electricity was passed through them at high voltage.

These 'Moore' lamps were brought into commercial use in 1907. They consisted of glass tubes about 200 feet long and nearly two inches in diameter. Different gases were used to give light of different colours; nitrogen, for example, emitted a golden light.

Moore lamps were the forerunners of the 'neon' lights that have since become so widely used in advertising and display. The rare gas neon is particularly effective, emitting a bright red light. Helium gives an off-white glow and mercury vapour is bluish white.

The light from these lamps is caused by bombardment of gas molecules in the tube by the electrons forming the flow of electricity. Forced along at great speed by the high electrical pressures, the electrons collide with gas particles and light is emitted. The efficiency of the light-production varies with the gas in the tube; argon and carbon dioxide, both giving a whitish light, are of poor efficiency. Neon gives a useful amount of light.

Although discharge tubes were developed and used in advertising before World War I, they did not become really popular until the 1920's. Since then they have established themselves as a familiar feature of our urban world.

The principle of the electric discharge through gases has been adapted to many forms of modern lamps. Electricity passing through sodium vapour sends out the baleful yellow light that illuminates so many British streets. Mercury vapour, on the other hand, emits a bluish light,

the wave-length mixture varying with the pressure of the vapour in the tube.

In street lighting the actual composition of the light is not of supreme importance. Sodium lamps emit their light almost exclusively in two precise wave-lengths in the yellow region of the spectrum. The world changes colour dramatically in this yellow light, but for street-lighting this does not matter unduly. But sodium vapour lamps would have a ghastly effect if used for lighting in the home.

Since World War II great progress has been made in discharge lamps, and the light emitted by them can now be adapted to suit all manner of purposes and conditions. With the help of luminescent substances discharge lamps have now been brought into domestic use.

When electricity is flowing through a gas at low pressure much of the radiation produced is in the ultra-violet region. The wave-lengths are too short to be visible. The proportion of ultra-violet light depends upon the conditions under which the discharge is flowing.

This ultra-violet radiation represents a waste of energy so far as light-production is concerned. But ultra-violet rays are absorbed by luminescent substances which, in return, emit visible light radiations.

By coating the inside of a discharge tube with luminous material the ultra-violet rays emitted by the discharge are converted into visible light. The colour of the light can be modified and controlled by using different types of luminescent substances. And in modern discharge tubes the light emitted is very similar to daylight.

The successful development of these modern types of 'fluorescent' lights has been made possible by strict control of the luminescent substances. Purity is vitally important; one part of impurity in a quarter of a million parts of luminescent substance will often have an impressive effect on the way in which it reacts to stimulation by ultra-violet rays.

Since the end of World War II fluorescent lamps have

been making rapid progress in industrial and domestic lighting. They are more efficient than the filament lamp in that they return more of the electricity they use as light. Some fluorescent lamps use only one-third of the electricity needed by a filament bulb giving the same amount of light. The tube-life is three times or more the life of a filament bulb. And the light from a fluorescent lamp is more like the daylight that we seek to replace.

There seems little doubt that discharge tubes will, in due course, take over from filament bulbs the job of lighting the world. They are taking us a step nearer towards the efficiency in light-production that is demonstrated so casually by insects like the firefly.

8

Life and the Rhythm of Light

We human beings know well enough when winter is on the way or when the spring is due again. Our lives are lived to a rhythm that is controlled by the calendar. But plants and animals live a seasonal life too, even though they cannot regulate their lives by looking up a diary. Instead, they check on the time of year by measuring the hours of sunlight that they enjoy from day to day.

No matter how inconsequent the weather may be, we still find Nature planning out her year with typical efficiency; the plants and animals settle down for a quiet spell in winter and awaken to a frenzy of activity in spring.

These seasonal activities go on with clockwork regularity. In the world of plants the primrose carpets the woodland floors in spring, and the daffodils follow close behind. As summer comes the hedges and gardens are splashed with the colours of innumerable summer-flowering plants. And in autumn chrysanthemums and Michaelmas daisies carry the fading colours of summer as leaves are starting to flutter from the trees.

Animals follow a similar pattern of seasonal activity. In the spring animals begin their family-raising. Nests are built and lambs are born; insects appear again as though from nowhere; swallows return from their winter quarters in South Africa; the hedgehog and the dormouse waken from their long winter's sleep. Through the summer months the animal world is at its busiest. Growing families have to be raised and fed, and sent out into the world. Then, as

autumn comes, the animals prepare for winter again. The swallows fly away, and flies seek out somewhere to settle down; hibernating animals look for a quiet resting-place; bees prepare to stay in their hives until the flowers appear again.

These seasonal activities of plants and animals go on with remarkable precision throughout the year. Yet living things have no calendar to tell them what month it is. The apple-tree does not know that November has arrived and it must drop its leaves; birds cannot realize that it is April or May, and time to lay their eggs; sheep do not select a certain calendar month in which to breed, so that the lambs will appear in spring.

How, then, do the plants and animals conduct their seasonal routines without the benefit of the calendar used by human beings? Scientists and philosophers have asked themselves this question for hundreds of years. But it is only within the last forty years that an explanation has been found. It is now known that plants and animals can organize the rhythm of their lives according to the length of daylight they perceive. If the days are short they know that it is winter; if the days are long they know that summer has come.

This method of assessing the time of year is essentially the same as that we human beings use in working out our calendar. Our year is a measure of the time taken for the earth to make a compete trip round the sun. The position of the earth at any time controls the length of day at any place; in Britain we have our shortest winter days in December and our longest days in June. The length of day increases and decreases steadily between these seasonal extremes. If we did not possess a handy calendar we too could organize our seasonal activities by measuring the length of day.

By using daylight as a guide plants and animals can be sure that there is no mistake in their estimate of the time of year. The length of day is not affected by any of the

vagaries of the weather. An Indian summer does not upset the seasonal arrangements made by nature, nor does an extended winter dislocate the programme organized for spring.

This light-controlled precision is essential to the survival of all livings things. Plants must arrange for seeds to germinate at a time when the weather for months ahead will enable the seedlings to survive; animals produce their young in the spring or early summer, so that they can learn to fend for themselves during the mild summer weather.

Before this discovery of the effect of daylight was made it was commonly believed that plants and animals responded to the changing temperatures of the season. Some plants, like the tomato, do in fact flower without being concerned about the time of year. Flowering follows automatically when the plant has reached a certain stage of growth. All that we have to do to bring tomatoes on is to give them plenty of warmth and food; as soon as the plants are big enough they will flower at any time of year.

These 'seasonless' plants encouraged the belief that temperature controlled the seasonal behaviour of plants. But it is now known that plants can be divided into three classes, depending on their reaction to the length of day. First, there is a group of plants, including tomatoes and cucumbers, which is indifferent to the length of day. As soon as they have reached a certain stage of maturity these plants will flower. Potatoes and bulbous plants belong to this group. They will begin to produce flowers even when grown in total darkness.

The second group of plants, including our autumn-flowering annuals, will flower only when the day-length falls below a certain number of hours. During the summer months they simply go on growing, waiting for the days to shorten so that they can start to produce their flowers.

In the third group, we have plants that flower only when the day-length is greater than a certain number of hours.

These are the summer-flowering annuals and biennials.

This discovery that plants divide themselves into day-length classes has cleared up a lot of the age-old mysteries of flower-growing. It explains how some plants will not flower at all in certain districts, even though they grow vigorously. It accounts for the ability of plants of the same species to flower at the same time, even though they are planted at different times during the season. It explains how nature keeps up her procession of flowers throughout the growing season.

But with this superficial 'explanation' we still have to be content. Nobody yet understands how the plant is able to check up on the length of day and decide when the time has arrived to start producing flowers. Hundreds of experiments have been, and are being, carried out, and we are learning a little more every day. But Nature does not give up her secrets easily.

It is now known that the light-detecting is done by the plant's leaves. When the leaves are covered up any other part of the plant can be subjected to its preferred day-night rhythm, but it will not flower. If all the leaves but one are covered, and this is given a suitable day-length treatment, it will stimulate the entire plant to flower. In some cases less than an eighth of a single leaf can bring on flowering if it is given the correct day-length treatment.

A leaf which has been given a flowering day-length treatment can be grafted on to a plant kept under a non-flowering light cycle, and the plant will flower. Six plants, each with a pair of stems, have been grafted one to the other to form a continuous line. Kept under a non-flowering light-cycle, the plants flowered in succession, one after the other, when a single light-stimulated leaf was grafted on to one of the end plants.

As evidence of this sort has built up it has become fairly certain that flower-production in the plant is under some sort of chemical control. Given the correct day-length stimulus, the leaves can manufacture some substance that

travels through the liquid-carrying vessels of the plant. When it reaches the growing points of the plant this substance stimulates the multiplying cells in such a way that they switch over from vegetative growth to flower-manufacture. Although this substance has not yet been extracted or identified, it has been given a name, florigen.

As research has continued the whole business of flower-control becomes more and more complex. It is now known, for example, that the plants are more interested in the length of the night than in the length of day. Under natural conditions the two are complementary; a short day means a long night. But we can alter nature's rhythm of night and day with the help of artificial light.

Chrysanthemums, for example, can be prevented from flowering simply by giving them a little bit of extra light during the long autumn night. This break in the darkness, which may be only a matter of a few seconds, can persuade the plant that the long nights have not yet arrived. And it does not flower.

Light-control of this sort is being used commercially by growers to control the flowering season of their plants. Chrysanthemums 'wakened up' by a minute or two of light in the middle of the night are unable to flower. Vegetables like spinach can be prevented from bolting by keeping them on a seven-hour day.

The most extraordinary thing of all is the plant's ability to remember past experiences of day-night rhythm. Soya beans, for example, will remember to flower when they reach maturity if they have gone through only two successive short day-long night periods during their early days.

With the help of its mysterious florigen, the plant has devised a chemical memory.

Inevitably this discovery of a light-controlled seasonal routine in plants has led to a search for similar routines in animals. And it has been found that many animals respond to the length of day.

In 1923 it was discovered that the sex life of certain

aphids is influenced by the rhythm of night and day. Five years later a series of experiments carried out by A. F. Shull showed that the growth of wings on the potato aphid could be controlled by subjecting the animal to certain rhythms of night and day. Young aphids would be born with wings only if their parents were provided with twelve to fourteen hours of darkness in their daily life routine. If the period of darkness was less than twelve hours or greater than fourteen hours the young aphids would normally be wingless.

The effect of light on the aphid's parents is most crucial during the day before the young are born. All the aphid embryos have wing-buds at that time; but too much light can disperse the wing-buds before the young aphid is born.

During the early 1930's it was found that birds of the same species living at different latitudes could adjust their egg-laying season to their varied environments. They had some mechanism that enabled them to assess the time of year. Voles were found to do the same.

Pioneer work on the influence of light on animal breeding rhythms was carried out in Canada by Professor W. Rowan. Rowan found that a bird called the junco, kept in an outdoor aviary, would breed in the depths of winter if the length of its winter day was increased with the help of artificial light. It could be persuaded into thinking that spring had arrived, even though the temperature was 84°C. below zero.

Since the 1930's, when these experiments were carried out, the effect of light on birds has been confirmed. Starlings living in the West End of London are sexually more mature than birds living outside the city; the bright lights of the West End, the advertising signs and street lamps, have brought an added sophistication to the city dwellers.

The influence of day length has its effects on mammals too. Ferrets, which usually breed in summer, can be persuaded to breed in winter if they are kept in artificial light to simulate summer days.

As in the plant world, light is not the only factor of the environment that affects the life rhythms of different species. Frogs are affected by the amount of rain that is falling, and fishes will respond to temperature changes. Some bats can produce their young during the proper 'season' even though they live in pitch-dark caves where the temperature does not change appreciably throughout the year.

The seasonal rhythms of animals are controlled by various factors in their environment; but light is undoubtedly the most important of all. An animal will wait until the length of day tells it that the proper season is here before breeding or building a nest or migrating.

For centuries Japanese bird-fanciers have encouraged their pets to sing in winter by keeping them in artificial light. In many parts of the world hens have been kept in lay by lengthening their winter days with the help of a lamp. These age-old techniques were putting the light rhythm to practical use, long before scientists knew anything about it.

Experiments carried out since World War II have shown that the quail matures only when the day length reaches a definite number of hours. It is a long-day bird and can produce eggs only after it has experienced a period of late spring or summer days. Starlings and ferrets, similarly, are long-day creatures; sheep, on the other hand, wait for the short days of autumn.

We know little enough of the way that day length operates in the plant world; but we know almost nothing of the details of its influence on animals. As might be expected, the light is perceived, at least in some animals, by the eyes. The stimulus is sent from the eye to the pituitary gland, situated at the base of the brain. This gland liberates a hormone into the bloodstream which affects the sex glands and so influences the breeding rhythm.

How these light-length messages are received and trans-

mitted remains a mystery. Much of the research carried out so far has been concerned with ferrets; we do not know how day length influences other animals of greater practical importance. We do not know how it affects the biological rhythms of man.

It seems likely, though, that the increased fecundity of inhabitants of tropical countries may be influenced to some extent by extra day-length. It seems most probable that the lengthening days of spring may play some part in the turning of a young man's fancy towards thoughts of love.

9

The Things Light does

When a stone is dropped on to the surface of a pond ripples spread out in all directions as the water moves up and down with a wave-like motion. Waves of light, similarly, are sent out through the ether from a candle or a lamp, or from the sun. But where the surface of water is flat and carries its waves in two dimensions the ether that carries light-waves is all-pervading; the ripples of light travel outward in three dimensions. If the wave-lengths were as big as those on a water-surface we should see them as spherical ripples spreading out in all directions from the source. They would look like a succession of balloons being blown up rapidly, one inside the other, expanding at great speed as they spread out into space.

Left to themselves, these spherical ripples of light will continue on their way through space for countless millions of years, travelling at their customary speed of about 186,000 miles a second. The farther they travel, the less powerful they become; the energy in each spherical ripple is spread over an expanding area, so that the effect of the light ripple on any surface it meets diminishes as the distance from the source increases. A light looks dimmer the farther away we get from it.

Light that reaches us from the sun has travelled 93 million miles on its journey through space. The sun's radiations are sent out in all directions, and our earth intercepts only a very small fraction of the total output. We tend to think of the sunshine as something that is provided exclu-

sively for man's delight. But in fact we share it with our neighbours in the universe. As it reaches us here on earth, light from the sun is so obviously being emitted as a stream of something or other that we treat it automatically in terms of 'rays.'

Light striking a house, for example, is partly absorbed by the tiles and bricks, which transform its energy into heat. The light that misses the house, skirting the roof and walls, continues on its way towards the ground. A shadow is left, marking the area where the house has absorbed the sun's rays. And the edges of the shadow are sharp, drawn as though the light was travelling in well-defined straight lines from the sun.

Since the days of Ancient Greece we have become accustomed to thinking of light in these terms. It is easy and convenient to use a 'corpuscular' theory for everyday purposes. Light is obviously a stream of something fired like a jet outward from its source. It travels a straight-line path, so that anything in its way casts a sharp shadow.

In everyday life this straight-line travel of light is so self-evident that we never give it a thought. If we have three screens, each with a hole in it, we know instinctively that if all the holes are in line we can shine a light through them and see it at the other end. But if the middle screen is moved so that the hole is not in line with the other two the light cannot be seen; it cannot bend as it leaves the first hole, make its way through the second one, and then bend round again to enter the third.

This straight-line travel of light has been accepted as a fundamental fact ever since light was first studied scientifically. We know now that it is not so factual as it might be. But for practical purposes we can regard light as something that moves outward from the source in straight lines.

This straight-line travel of light was one of the rocks on which the corpuscular theory of light was built. Sir Isaac Newton, faced with a choice between a corpuscular theory and a wave theory, could not see how a wave theory fitted

in with the fact that light travels in straight lines. If it was in the form of waves, he argued, light would spread outward as it passed through a hole in a screen. Waves on the surface of the sea, passing through a small opening in a breakwater, do not continue as a 'ray' of waves the width of the opening. They spread out as they emerge, handing on their vibrations in all directions to form a semicircular pattern just as though the hole was the source of the vibration.

If light is a wave motion, said Newton, why did it not spread out in this way on passing through a hole in a screen? Although Newton's doubts could not be answered satisfactorily at the time, we now know that his argument was unsound. Light does, in fact, spread out as it emerges from a hole. But under normal circumstances the hole is so large by comparison with the wave-length of the light that the spreading effect is not noticeable. Everything depends upon the size of the hole relative to the wave-length of the vibrations.

If a succession of small parallel ripples is raised on water and allowed to pass through a large hole in a barrier most of the waves continue to move forward through the hole in their original direction; only the ripples near the edges of the opening are affected by the barrier and are turned outward. A 'ray' of ripples is formed, only the edges being disturbed.

If the size of waves is increased, however, so that the wave-length becomes comparable with the width of the opening in the barrier the 'ray' effect is destroyed. The waves emerging from the hole no longer have a middle region that it unaffected by the barrier; the emerging wave no longer travels forward as a ray with blurred edges. The entire movement of the ripple has been affected by the barrier edges, and the emerging waves continue in a semicircular path from the opening.

These waves that travel over the surface of the sea are large enough for each individual vibration to be visible to

the naked eye. The distance between successive crests, the wave-length, may be several inches or even feet. Under normal circumstances these waves are affected by openings and obstructions comparable in size with the wave-lengths of the undulations.

But in the case of light waves we are dealing with vibrations in which the wave-length is between sixteen and thirty-two millionths of an inch. In any 'ray' of light such as we make by passing light through a hole in a screen the dimensions of the hole are thousands or even millions of times as large as those of the waves. Any spreading of the waves at the edges of the hole has only an insignificant effect on the forward progress of the bulk of the waves in the ray of light. Under normal circumstances we cannot even detect any spreading of this sort at all.

If, however, we pass light waves through slits so narrow that they are comparable in width with the wave-lengths of the light the spreading effect becomes as noticeable as it does when waves travel past obstructions on the surface of the sea.

This bending of light as it passes an obstruction is called diffraction. The angle through which the light is bent depends upon the wave-length of the light; the longer the wave-length, the more the light is deflected from its original path. Visible light, with its mixture of waves of different length, tends to be separated into its constituent colours as it passes the edge of an obstruction. The long-wave red rays are turned aside more than the short-wave violet rays.

Though Sir Isaac Newton regarded the straight-line travel of light as support for the corpuscular theory, he knew of this phenomenon of diffraction. He repeated experiments that had been carried out by Grimaldi, a Jesuit professor of mathematics at Bologna. Grimaldi had noticed that the shadow of a rod held in a beam of light was not as well-defined as it ought to be. He found that the edges of the shadow were blurred by coloured bands

of light and suggested that the light had been bent as it skirted the edge of the obstacle.

Newton confirmed what Grimaldi had discovered, but remained convinced that light was a stream of particles. He believed that waves would have been bent as noticeably as are waves on water; the slight deviation that in fact took place was due, he said, to some sort of attraction exerted by the edge of the obstacle on the moving particles.

In 1880 Dr Henry Rowland, of the Johns Hopkins University, in the United States, used diffraction as a way of splitting light into its colours more effectively than could be done in an ordinary glass prism. He made an instrument called a diffraction grating.

In principle the diffraction grating is extremely simple. It is a piece of glass on which a series of parallel lines has been ruled—as many as 30,000 to the inch. As light passes through the transparent slits between the lines part of it is diffracted and bent to either side of its previous route.

The diffraction grating is made with such accuracy that rays of the same wave-length are all deflected through the same angle by each slit. Light passing through the grating is split into its component wave-lengths, forming a spectrum of colour. If the light is a narrow beam it throws a series of lines on a screen, the position of each line being determined by the wave-length of the light that has produced it. A diffraction grating acts in this way like a glass prism, but it can separate the constituents of light much more efficiently than a prism. Sunlight, for example, can be split into 100,000 different ' colours.'

If it is to be of real value a diffraction grating must be made with extraordinary precision. The lines must be accurately parallel and equally spaced. The ruling engine perfected by Professor Rowland in 1880 was a masterpiece of fine engineering and has served as the prototype of similar engines operating in other countries to-day.

Lines are scratched on an inch-thick glass by a diamond

that is drawn time and time again over the surface. Each time the diamond passes over the surface the glass is shifted forward by one thirty-thousandth of an inch until a six-inch-wide surface has been marked by 180,000 almost invisible scratches. These scratches, so close together that twenty-five could be drawn on the edge of a piece of cigarette paper, act as the opaque part of the grating. Often lines are ruled on a highly-reflecting metal surface, so that the waves are reflected instead of being transmitted. But they are bent in exactly the same way to form a spectrum.

These gratings have replaced the prism in modern spectroscopes, enabling us to split up light into its component wave-lengths with great accuracy. By examining the lines on the spectrum thrown when light is diffracted by a grating we can identify elements that are sending out their characteristic ' finger-print ' wave combinations.

Many of the most beautiful colours displayed by living things come from light that is separated into its constituent waves by diffraction. Light falling on to a finely grooved surface is reflected and separated in the same way as light passing through a diffraction grating.

The metallic blue of a beetle or butterfly is caused by light that is separated and thrown back in different directions from the finely grooved surface of the insect's body. The arrangement of the grooves is such that we see blue when we look at the insect from above. But the other colours can be seen if we look from the appropriate angle; a butterfly's ' blue ' will appear crimson when looked at along the surface of the wing.

This type of colour is entirely different from the colour that is due to selective absorption of some of the constituents of the white light falling on a surface. The colour of a beetle can be destroyed, for example, by filling the grooves on its body with oil. But they return when the oil is wiped away.

If a soft wax is pressed against the blue wing of a butter-

fly the wax itself will acquire the insect's colour. Not because it has absorbed any pigment from the butterfly's wing, but because it has taken an impression of the light-deflecting grooves that split up the light into its different constituent wave-lengths. If the surface of the wax is smoothed with a knife blade the colours disappear.

The bending of light by diffraction is a phenomenon that we do not recognize often in everyday life. But there is another way in which light is bent that is so familiar as to be commonplace. Light changes its direction of travel as it moves obliquely from one transparent medium to another. This bending of light as it goes, for example, from air to water is called refraction. It is refraction that makes a stick look bent when we hold it in the water of a pond. Refraction bends the light entering the lenses of our microscopes and telescopes, and makes almost all our optical instruments possible.

Refraction can best be understood by thinking of light in terms of waves. Sunlight can be regarded as a succession of almost ' flat ' pulsations following each other so rapidly that there are tens of thousands of crests to the inch. These waves travel at constant speed through space, no matter what the wave-lengths of the various constituents may be. All the colours in visible light therefore arrive at the same time.

But light travels at different speeds in different transparent substances. In glass, for example, it is only two-thirds as fast as in air; in water, light travels at three-quarters of its speed in air.

Suppose that a wave advancing through the air meets a glass surface. If it strikes the glass vertically, so that all the wave leaves the air and enters the glass simultaneously, the progress of the wave is slowed. But it continues to travel in the original direction.

Suppose, however, that the wave strikes the glass surface obliquely. The edge of the wave that enters the glass first is slowed up, but the rest of the wave continues at its

original speed through the air. As the wave front moves farther into the glass the slowing-up process continues until eventually the entire wave front has been transferred from air to glass. By this time the wave has been 'slewed round'; the part that entered the glass first has travelled a shorter distance in the glass than the other end travelled during its extra time in the air. The direction in which the wave front was travelling has been changed. Once the whole of the wave is again moving at uniform speed inside the glass it continues on its way in its new direction.

This bending effect can best be visualized by two-dimensional analogies. Suppose, for example, that a regiment of soldiers marching over smooth grassland were to come to a ploughed field. If they were marching in such a direction that all the front rank arrived at the edge of the field at the same time the soldiers would all be affected simultaneously. Progress would be slowed, but there would be no change in direction.

If, on the other hand, the front rank reached the edge of the field obliquely one end of the rank would be slowed before the other. As each man entered the field in succession, he would march more slowly, and by the time the last man in the front rank was in the ploughed field the regiment would be marching at an angle to its original direction.

The bending of light by refraction has been put to practical use in the optical device we call a lens.

A simple lens is a disc of glass with two surfaces curved so that the glass is thicker in the middle than it is round the edges. When a flat wave front reaches the surface of a lens the centre of the wave enters the glass first and is immediately slowed. As the wave continues on its way more and more of it enters the glass from the air at increasing distances from the centre of the lens. By the time that the whole wave has entered the glass it has become curved. Instead of being flat, it is saucer-shaped. The centre part travelling for a longer time in the slower glass

is lagging behind the outer edges which have travelled longer in the air.

As the saucer-shaped wave continues on its way through the glass it reaches the other side of the lens. The outer parts of the wave front leave the glass before the inner parts, so that the wave becomes even more saucer-shaped than it was inside the lens.

If the lens has been designed properly the saucer-shaped wave converges to a point outside the lens. All the light that enters the lens from any point source is concentrated at a corresponding point on the opposite side of the lens. That is to say, the light comes to a 'focus' at this point.

Just as the wave theory of light enables us to visualize what is happening when light is bent by diffraction or refraction, so can it explain other phenomena associated with light. It gives us a satisfying explanation, for example, of the coloured rings and bands that are formed when light falls on to very thin films and solid layers.

If a beam of light strikes a thin, transparent plate rays are reflected from the top surface and also from the lower one. If the 'hills' of one reflected ray coincide with the 'hollows' of the other one the waves will cancel each other out so that there is no 'light' at all. But if the wave crests and hollows are in step the vibration is reinforced.

Light of a single wave-length reflected by a thin plate sends out two sets of reflected waves in this way. At various positions on the plate the rays get into step and out of step so that alternate bands of light and dark appear, causing the phenomenon we now call 'interference.'

If the source of light is sending out a mixture of rays such as we get in sunlight the interference of various wave-lengths is controlled by the thickness of the film. In a soap-bubble or a patch of oil on a road the film varies in thickness, so that interference affects light of different wave-lengths in different parts of the film. We therefore see interference patterns in rainbow colours.

This phenomenon of interference is used by nature to

create some of the most beautiful of all her colour effects. Many insects are coloured by interference caused by thin transparent layers, as are the feathers of brilliant-coloured birds such as the parrot and the peacock. The iridescent colours of pearls are caused by interference in the light reflected from the layers of transparent substance secreted by the oyster to form the pearl.

The strange effect produced when light shines through crystals of Iceland Spar can also be explained when light is regarded as waves. The waves sent out from a luminous source will normally be vibrating in all directions across the direction of travel. In a beam of light shining parallel to the ground, for example, there will be waves vibrating vertically and horizontally and at every angle between the two.

When a beam of light shines into a crystal of Iceland Spar so that two separate beams are formed the serried ranks of atoms and molecules forming the crystal are distinguishing between waves vibrating in different planes. The waves moving up and down, for example, are bent in one way, and those moving from side to side in another way. Light emerging from the crystal is vibrating in one plane, rather than in all possible planes as in ordinary light. In one of the twin beams of light that comes from the crystal of Iceland Spar the waves are vibrating in one direction across the beam; in the second beam they are vibrating in a plane at right angles to the other one.

By cutting a crystal of Iceland Spar suitably one of the beams can be deflected to one side, so that only a single beam emerges. This beam, with all its waves vibrating in one plane, is described as being 'polarized.'

Light that has been 'plane-polarized' by passing through a crystal of Iceland Spar looks exactly like an ordinary beam of light. The human eye is unable to distinguish between waves vibrating in one plane or another. But other creatures have eyes that make excellent use of it to guide them about the world.

10 The Wonder of Vision

When light falls on the world around us it is reflected to and fro by all the things it meets. Every surface deals with light in its own characteristic way. Some of the light may be absorbed and transformed into heat or other forms of energy; the rest is thrown back as reflected light that continues its travels until another surface is reached. Everything on earth is bathed in light that reaches it from all directions and is bounced back at every conceivable angle from its surface. This reflected light is used by living creatures as the basis of a long-range object-locating system. It has made possible our sense of sight.

When we 'see' the printed words on the page of a book we are detecting and assessing the rays of light reflected by each infinitesimal part of the page. The rays that happen to reflect in the direction of the pupil of each eye from every part of the page are absorbed; the strength of the light and the direction from which it comes are estimated, so that the eye builds up a composite pattern of light of different strengths coming from every part of the scene before it. Moreover, it can distinguish between the various wave-lengths in the rays, each wave-length causing a different stimulus that we recognize as a characteristic colour.

This pattern of light picked up by the eye is relayed in the form of electrical impulses to the brain. Every instant the brain is receiving electrical information that it can interpret to provide a 'picture' of the ever-changing scene.

Light is the information-carrier that makes this sense of vision possible.

The detection and measurement of light rays coming from all directions is a formidable task, and the human eye is an instrument of wonderful precision and ingenuity. It combines the principles of photography and television, concentrating them into a sphere of tissue only an inch in diameter and adding innumerable refinements of technique that leave us bewildered by their beauty.

As light reaches the human eye it passes first through a curved window of transparent tissue, the cornea. This layer of living matter is devoid of blood-vessels that would get in the way of the light; it is bathed with watery liquid that flows from the tear-ducts above the eye. Every few seconds the eyelids blink and smear a layer of liquid over the cornea to keep it moist, excess liquid drains away through tear-ducts in the inner corner of the eye. As the eyelids blink they act as windscreen wipers, removing dust or dirt that might damage the eye. They also act as shutters, flashing across the cornea in a fraction of a second when anything is moving rapidly towards the eye. The liquid that they smear across the cornea contains a powerful antiseptic, lysozyme, which destroys any germs that might otherwise damage the eye. It carries food substances to the tissues of the cornea, which is not in contact with the blood-stream.

Immediately behind the cornea is a watery liquid that fills the front part of the eye. Light travels through this liquid towards the iris, which is a ring of coloured tissue that limits the size of the hole through which light can enter the rest of the eye. The iris is controlled by a fringe of muscles which can enlarge or diminish the hole in the middle. This hole is what we call the pupil of the eye.

In brilliant light the eye must allow only a limited amount of light to enter; otherwise the detecting mechanisms would be swamped with light. The iris therefore closes automatically when the scene before us is too bright.

By permission of Mrs Bethia Foott

A LUMINOUS FUNGUS

This photograph of *Pleurotus lampas*—the "Ghost Fungus" —was taken by the late Colonel Allan Foott, using only the 'living light' emitted by the fungus itself.

Photo Shell Photographic Unit

THE EYES OF A FLY

Hundreds of tiny lens-units are built up into huge domes that cover a large area of the head.

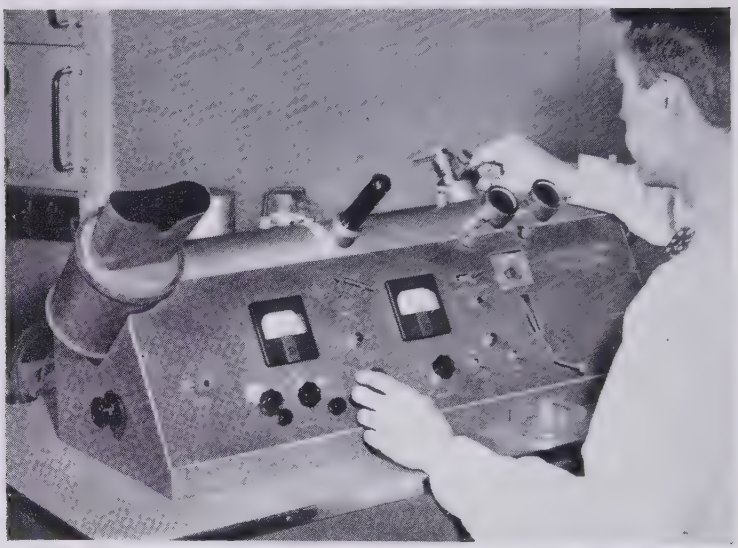


Photo General Electric Co.

ELECTROSTATIC ELECTRON MICROSCOPE CONTROLS

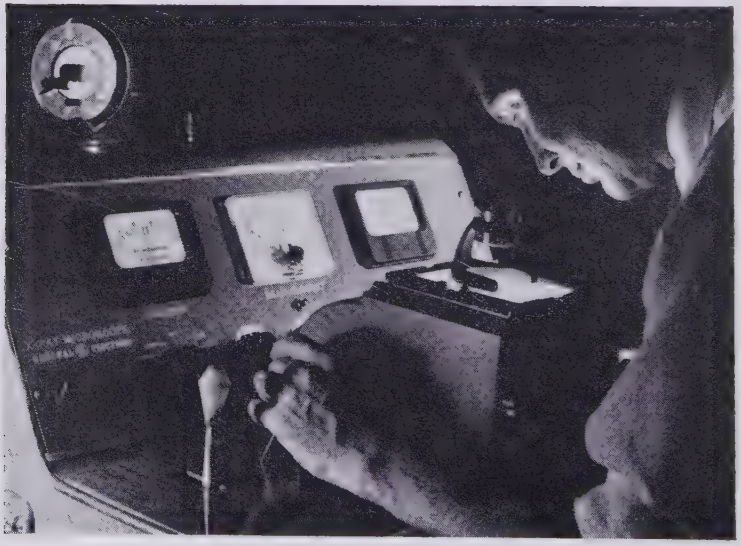


Photo General Electric Co.

AN X-RAY MICROSCOPE IN USE

The pupil becomes little more than a tiny dark spot. But in dim light, when the eye is struggling to detect radiations thrown back from surfaces that have little to reflect, the iris opens wide and the pupil is large. It is allowing the eye to collect as much light as it can from the small amount available.

Immediately behind the iris is the lens. This is a little disc of transparent, elastic tissue that concentrates the light coming through the hole in the iris, bringing the rays together so that they come to a focus on the sensitive layer at the back of the eye.

Without its lens, the eye would be unable to analyse the strength and direction of the light coming from the scene in front of it. The picture looked at by the eye consists of millions of separate, tiny pin-point areas, each reflecting a certain amount of light of definite wave-lengths. These radiations are being thrown out by each pin-point area in many directions round it. Those that happen to travel in the direction of the iris-hole are able to enter the eye; the bigger the hole the greater is the ration of light emitted by each point source that can enter the eye.

The stream of light rays passing through the iris-hole from any point area of the scene is in the shape of a long, thin cone, like an elongated dunce's cap. The pin-point source is the point of the cone and the iris-hole is the base.

If this cone of light rays was allowed to continue its journey unaltered towards the back of the eye it would fall on the sensitive surface as a patch of light even larger than the hole in the iris itself. If the eye was concerned only with a single point source of light, it could measure the amount of light in the patch and its wave-length, and also estimate the direction from which it reached the eye.

But in any ordinary scene there are countless numbers of pin-point sources all sending out rays of different strength and wave-lengths, and all reaching the eye from different directions. Each pin-point source is forming a cone of rays with the iris-hole as a base; each would throw

a patch of light bigger than the iris-hole on the back of the eye.

Under these conditions the back of the eye would be stimulated by a pattern of light formed from innumerable large patches of light of different brightness and wave-length, all overlapping one another. The individuality of the rays from each pin-point source would be lost in this kaleidoscopic welter of light; there would be no way of sorting out the pattern of impulses to provide a coherent reproduction of the scene.

The lens of the eye is used for bringing order out of the chaotic jumble of light rays travelling through the iris-hole. As the light from any pin-point area of the scene falls on to the lens it is in the form of a circle of light; it is the base of the cone of radiation formed by the round hole of the iris. The lens bends the rays of light in such a way that they are all brought together again to a point, forming another cone with the same base as the original cone, but with the point on the opposite side of the lens. This point where the light comes together is called the focus.

The focus of the light rays coming from any pin-point area of the scene in front of the eye consists of a corresponding pin-point of light on the other side of the lens. The brightness of the light at the focus, and its wave-length, depend on the brightness of the pin-point source and the wave-length of the rays sent out from it. The position of the pin-point of light at the focus is controlled by the direction from which the light rays strike the lens.

When we imagine any scene as made up of millions of separate pin-point areas, each reflecting light of a definite brightness and wave-length, we can see that a lens can bring the light from each pin-point area to a focus behind it, forming a pattern of light corresponding to that which is providing the light. These pin-points thrown by the lens will merge together, forming a picture identical with that which sent out the innumerable tiny areas of reflected light towards the lens.

This is what the lens does inside the eye. The picture it builds, the image, is brought to a focus with great accuracy on to the sensitive layer at the back of the eye, providing us with a reproduction in miniature of the scene before us.

In a lens of fixed shape the light is brought to a focus at a distance which depends on the distance of the object providing the light. The nearer the object is to the lens, the farther away the image will be from the lens. We can alter the distance of the image from the lens by altering the curvature of the lens surfaces. The more convex the lens, the nearer is the image to it.

The lens of the eye is built from elastic tissue and is held by ligaments attached to its rim. Normally these ligaments pull at the lens, keeping it fairly flat so that the eye focuses on things more than six yards away. When we want to see something closer than this the pull of the ligament is relaxed; the elastic lens tissue contracts to a fatter, more curved shape. In this way we can bring light from almost any distance to a focus on the back of the eye; we can see a star millions of miles away in the sky, and then adjust our eyes instantaneously to read a book a few inches away.

So the shape of the eye-lens at any time controls the distance at which the things we see are in sharp focus. The object of our attention is focused accurately, but anything farther away or nearer tends to be vague and blurred. The light coming from any pin-point area at these distances is forming overlapping circles of light on the sensitive eye surface, rather than pin-points. The smaller the hole in the iris, the smaller the patches of light will be; we see things 'out of focus' more sharply in bright light than we do when the light is dim.

The comfortable position for the lens of the eye to assume when we are scrutinizing something in detail is such that it focuses rays from a distance of ten inches to a foot from the eye. This is the position we tend to use when reading a book. As we bring things nearer to the eye we reach a point where the lens is unable to adjust its shape

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any farther to focus the light accurately. We can 'see' print an inch or two in front of the eye; but the cones of light from it are forming patches instead of points on the light-detecting surface, and our vision is blurred.

Defects of the eye are commonly caused by an inability to adjust the lens of the eye over part of its range. When we cannot flatten the lens enough we are unable to focus objects a great distance away; when we cannot make the lens fat enough we find difficulty in seeing things close to our eyes.

As people grow older the lenses of the eyes grow bigger, and the tissue becomes tougher. The muscles attached to the lens cannot change its shape so easily as they could before. After the age of about forty-five many people need glasses to make up these deficiencies in the lenses of the eyes; others find that changes in the lenses have improved the sight to such an extent that they can dispense with glasses that they had to wear before.

The lens is the most important light-controlling mechanism of the eye. It collects and concentrates the rays and throws them in a definite direction. But most intricate and delicate of all the parts of the eye is the layer of sensitive material that translates the image from the lens into the impulses that give us our sense of sight. This job is the responsibility of the retina.

As it leaves the lens light travels through a viscous fluid that fills the centre of the eyeball; it comes to a focus on the layer of sensitive cells that line the inside wall of the rear of the eyeball. This is the retina, where light is converted into electrical impulses that are sent off to the brain.

Though the retina is less than one-hundredth of an inch thick, it is a complex tissue built from nine layers of cells. Light is absorbed by two distinct types of cell, some of them shaped like rods and the others like cones. There are about 132 million of these light-sensitive cells in the human eye. Each one is connected to the main optic nerve

by fibres that carry the electrical impulse created by light falling on the cell.

By lining the retina with millions of separate light-sensitive cells Nature ensures that the precision and accuracy of the eye-lens is not wasted. If the retina was made from only a few large sensitive elements each one would be stimulated by light from a comparatively large area of the scene surveyed by the eye. The brain would receive an electrical impulse from each sensitive cell that described only the average light conditions in the area of the scene focusing on this particular part of the retina. The 'picture' built up by the brain would be correspondingly vague.

The more sensitive cells there are packed into the retina, each with its own nerve-connexion, the more detailed is the light information that can be used by the brain.

The work of the eye is divided between the two sorts of sensitive cell. Cone cells are responsible primarily for dealing with the bright light of day, and for distinguishing colours. They look after the detailed analysis of images formed by the lens, and, in the human eye, are concentrated in the central region of the retina. Here, where the main image normally falls, the cone cells are packed together, enabling the brain to receive precise information about the light pattern that is entering the eye.

The rod cells are concerned almost entirely with vision in dim light. Lying outside the central area of the retina, they are sensitive to extremely low levels of illumination; they are the cells that enable us to see at night. But they have no way of discriminating between light rays of different wave-lengths. In the dim light of near-darkness colours disappear and we live in a world of grey shadows.

We can often see things more clearly in the dark by looking at them out of the corner of the eye; in this way we focus the light on to the sensitive rod-cells that lie outside the central cone-cell region. Night-fighter pilots during the war were encouraged to search for the enemy

by looking to one side of the place where they expected his plane to be.

A great deal of research is being carried out on the processes that take place in the light-sensitive cells of the retina. In the rod cells conversion of light into electrical energy is made possible by a purple pigment that can be extracted from these cells. When light falls on this 'visual purple' the pigment is bleached and turns into a yellow substance. This then breaks up into a colourless protein and vitamin A. These chemical changes caused by light are accompanied by the release of electrical impulses that are sent off through the optic nerve to the brain.

Visual purple in the rod cells can be rebuilt from the protein and vitamin A by the reverse process in the absence of light. Without adequate supplies of vitamin A —the 'night blindness' vitamin—the body cannot manufacture the visual purple it needs for its ultra-sensitive rod cells. That is why night fliers were exhorted to eat plenty of carrots during the war. Carrots are rich in vitamin A.

In bright light, such as the normal light of day, visual purple of the rod cells is destroyed and vision depends on the cone cells. When we enter a darkened room from the light we are temporarily blinded. In the cinema, for example, we stumble towards a seat we can find only by touch. The rod cells of our eyes are bleached of visual purple, and the cone cells are inadequate in the dim light. Yet in a few minutes we begin to see the people around us; in half an hour we have recharged our rod cells with visual purple and are able to pick up the feeble lights reflected from our surroundings.

In a similar way the dazzling headlights of an oncoming car can cause temporary blindness by destroying the pigment in the rod cells we are using to see in the dim light. When we leave a dark room and emerge into brilliant light we screw up our eyes in an effort to protect their sensitive rod cells from the strong light. Then, after a few seconds,

the eye has adjusted itself; the iris closes to cut down the light and the cone-cells take over.

We know little yet about the light-sensitive processes that take place in the cone cells. Unlike the rods, which are content to accept light over a range of wave-lengths, the cone cells have to discriminate between one wave-length and another. In this way they enable us to live in a world of colour.

Experiments carried out by Professor Granit in Sweden have shown that some animal eyes contain several types of cone cells, each type sensitive to definite wave-lengths of light. Fibres leading from the sensitive cells in the eyes of anæsthetized animals were isolated and connected to amplifying equipment. Light of different wave-lengths was shone into the animal's eyes, and the electrical responses measured.

These experiments have shown that there are at least seven types of light-sensitive cells in the eyes of some animals; each type of cell reacts to radiation of a definite wave-length. Some respond to orange, others to yellow, yellow-green, green, blue-green, blue, and violet. There are also cells that send out impulses when they receive light rays of any colour. It is believed that a similar system operates in the cone cells of the human retina, enabling us to distinguish between one colour and another. Defects in these colour-sensitive cells are responsible for some types of colour blindness.

Occasionally people suffer from a blindness caused by defective cone cells. They depend entirely on the rods for vision, living in a world that has no colour at all. Sometimes the cone cells work, but do not distinguish between one colour and another. Again, these people live in a colourless world, but one in which shades of brilliance and detailed shapes are more distinct.

Colour blindness often takes the form of unusual colour values, rather than an absence of any colour at all. People react to colours as though one or other of their colour-

detecting cells were out of action. This type of colour blindness is much more common in men than in women. It is often hereditary and passed by women to their offspring.

The influence of light on the sensitive cells of the retina does not disappear as soon as the light is turned off. The cells continue to 'see' the light for about a tenth of a second, causing the phenomenon we know as persistence of vision. In the cinema pictures are flashed in rapid succession on the screen, with intervals of darkness between each. Persistence of vision enables the eye to continue to see one picture until the next one has arrived on the screen, and we get an impression of continuous movement.

In a sense, the retina of the eye, lined with all these ultra-sensitive cells, is like a layer of brain spread across the rear of the eyeball. It is an outpost of the brain, translating messages carried by light and dispatching them electrically to the brain proper. Every instant of the day the brain is receiving millions of these impulses through the optic nerve. The messages from 132 million individual light-detecting cells are relayed through a million nerve fibres. Where they come together and leave the eye as the optic nerve, these fibres form an insensitive patch on the retina which is devoid of light-detecting cells. This is the blind-spot of the eye.

Though we naturally think of the eyes as forming windows through which the light passes to provide an image for our brain, we often forget that what we 'see' is only in the brain itself. The image on our retina, for example, is upside down, although the brain persuades us that we 'see' it right way up.

Efficient sight is as much dependent on the brain as on the eye itself. We can go blind even though the eyes are perfectly sound. And in the same way people with eyes that cannot perceive any light are able to 'see' pictures clearly in the brain.

The brain can, in fact, adapt itself remarkably well

to compensate for defects in the operation of the eyes. Scientists have worn special glasses fitted with mirrors to give an upside-down view of the world. After three days the brain has realized that some adjustment is needed to meet the new circumstances, and reversed the 'image' so that the world was seen right way up again. Similarly, the loss of an eye does not necessarily mean that the field of vision is reduced by half. The brain revalues the sensations that it gets from the single eye, and the single eye operates at as much as four-fifths of the efficiency of two.

If human beings were equipped with only a single eye, therefore, vision could be almost as good as it is with a pair of eyes. But Nature has given us two eyes to enable us to see in three dimensions, and to judge the distance of things ahead of us. Each eye sees an object from a slightly different point of view. The left eye looks at a ball about two and a half inches to the left of the position from which the right eye sees it. As a result the left eye sees round the ball a little further on the left, and the right eye sees a little further on the right. These two impressions are transmitted to the brain, which uses them to assess the 'solidity' of the ball and to estimate the distance it is away.

This technique of binocular vision is now known to be a good deal more complex than had been thought. Research has shown that our eyes are constantly on the move when we are looking at any object. Mirrors fixed to contact lenses on the eyes can show up even the smallest movement when light is reflected from them on to a screen. It has been found that our eyes will drift about and jerk suddenly from one place to another, moving usually in unison. But they also tremble at a rate of about ninety vibrations a second, and these fine movements take place independently. At any instant, therefore, the brain is receiving three-dimensional information from eyes that do not keep the images on the retinas a constant distance apart. The brain is even more nimble than we had assumed.

In one way and another the sense of sight in human

beings makes use of light with remarkable efficiency. The human eye can see particles of dust or the filament of a spider's web measuring only one-five-thousandth of an inch across. It can distinguish between wave-lengths varying from sixteen to thirty-two millionths of an inch. And it can adjust itself to examine objects many miles away as easily as it can read the print on the page of a book.

11

All Sorts of Eyes

MAN has learned to lean heavily on his sense of sight. The human eye, acting in concert with a highly developed brain, is able to keep us in continual touch with the world around. Yet the human eye is not the most efficient of all animal eyes; nor is it by any means the simplest. Many creatures have eyes that are more versatile or more sensitive than ours; some have eyes so primitive that they can do little more than detect the presence of light.

Throughout the animal world the sense of sight has reached many stages of development. Some animals, living in a world of perpetual darkness, have no need of sight at all; bats live in deep caves to which light does not penetrate; fishes swim in the waters of underground caverns; some parasites spend their lives buried inside the body of their host. To these creatures of the dark, daylight is a meaningless thing; they have learned to live without it. Often they have no eyes at all and are without even the most rudimentary organs for making use of light.

Many simple animals that live in our world of daylight and darkness have reached only the earliest stages in their progress towards the power of sight. Simple one-celled creatures, amœbæ, can sense when light is shining on them; some of them move towards the light, and others away from it. Somehow, inside the single cells of their bodies, these creatures are influenced by the light that shines on them; the light is absorbed, causing some chemi-

cal change that takes part in the living mechanisms that control the movement of the cell.

These simple animals can detect the presence of light and can assess the direction from which it comes. But they can do little more than that. They cannot use light to distinguish the shape of things around them; they cannot use light to follow the intricacies of movement in other living things, nor can they interpret the different wavelengths of the light in terms of colour. They are light-sensitive, but they can hardly be said to possess the power of sight.

As animal organisms become more complex so does their reaction to light become more sensitive and precise. Single-celled animals have such limited equipment that they cannot make much use of light at all; but many-celled animals can allocate the job of light-detection to special cells whose job it is to make the most of the facilities provided by light.

Sometimes these light-sensitive cells are scattered over the surface of the animal's body. The earthworm, for example, can see in all directions at once. Its light-sensitive cells pick up the radiations falling on any part of the body, so that the worm is able to move with respect to the direction of the light. As it wriggles out of the ground, the worm will know that its front end is in the light and its rear in darkness. But the worm will not be able to use its 'eyes' to look around and survey the scene as it leaves its burrow. It cannot really see in the sense that human beings can see.

The next step towards the development of a real power of sight is taken by animals which concentrate their light-sensitive cells into little patches on the surface of their bodies. These patches enable creatures like jellyfishes and marine worms not only to detect light, but to estimate with some efficiency the direction from which it comes. Also they can sense the movement of another living thing that swims across the field of view; light reflected from a

moving animal is perceived by a succession of different cells in the sensitive patch.

This is about as far as any animal can go when its reaction to light is restricted to the activity of a patch of sensitive cells on its body surface. To enable it to see in the sense that human beings see it has to resolve the confusion of light rays falling on its sensitive cells in such a way that they can stimulate the cells in a pattern that corresponds to the light pattern of the scene before it. Some arrangement is therefore needed for focusing light; the rays from each pin-point source of light in the scene must be brought together as a pin-point of light in a definite position on the patch of sensitive cells. The millions of pin-points of different brightness that make up the scene will then be reproduced in the same pattern on the patch of sensitive cells, forming an image of the scene. With the details of this image being relayed through its nervous system, the animal will be able to see. It will distinguish between friend and foe; its life will become more purposeful as it seeks for the food it recognizes with the help of its sense of sight.

Many marine invertebrates have adopted a simple technique for converting a light-sensitive patch into a seeing eye. The patch of cells is sunk into a cup-like depression on the surface of the body, leaving only a tiny hole through which light can shine on the sensitive cells. The limpet has an 'eye' of this sort.

By leaving a small hole for light to enter its eye the limpet restricts the sensitivity of its eye; only a small amount of light can enter from any pin-point source on the scene in front of it. But by way of compensation the small hole enables the limpet to bring order out of the chaotic mixture of light rays that reaches it; the hole itself acts as a lens.

Light coming from any point-source in the scene enters the limpet's eye through the hole, just as it enters the human eye through the pupil in the centre of the iris. In

the human eye the pupil is a comparatively large hole. The light from any point-source of the scene forms a cone with the pupil as its base; left to itself, this cone of light would throw a large patch of light on the retina of the eye. And with millions of patches from all the point-sources overlapping the retina would receive a meaningless patchwork of light. But the lens in the human eye focuses each cone of rays, bringing them to a point on the retina. The image is therefore clear and sharp.

If the pupil of the human eye was a mere pin-hole there would be no need of a lens. The patch of light thrown by any pin-point source on the retina would inevitably be small. Only a comparatively few individual light-sensitive cells would be stimulated, so that the image as seen by the brain would be sharp.

This is the secret of the limpet's lensless eye. The tiny hole in the top of the depression allows only a narrow pencil of rays from each point-source of the scene to penetrate on to its 'retina' of light-sensitive cells. So the limpet can distinguish the outline of different shapes and can see its surroundings as a pattern of light and shade. It can recognize something that might serve as food.

The limpet, like many other marine creatures equipped with this lensless eye, can 'see.' But, like other invertebrates, it lacks the brain that could enable it to use its sense of sight in the way that vertebrate animals do. The impulses that are sent from the eye are received by groups of nerve-cells on the body and stimulate the appropriate responses. The sight of food will conceivably encourage a jellyfish to move towards its meal. But other things floating in the vicinity will have no meaning for the jellyfish. The animal may detect the movement of a man swimming past it. But the sight will convey nothing. Lacking a brain, the jellyfish cannot draw on the remembrance of past experiences; it cannot translate the impulses from its eye into something labelled 'man.'

This type of eye, little more than a depression in the

body surface lined with sensitive cells, is good enough to serve the simple needs of a limpet or a jellyfish. But it is inadequate for creatures with a more ambitious plan of life. The pin-hole system enables the limpet to create an image of what it sees, but the amount of light that enters from each part of the scene is so small that the image is dim. To let more light in and provide a brighter and more detailed picture the hole must be enlarged. And to retain good definition a lens is then needed to bring the rays to a focus on the retina.

The higher invertebrates, such as the octopus or the snail, have abandoned the simple pin-hole eye. A layer of transparent tissue covers the hole and is curved and thickened to form a simple lens. Light striking the eye is bent and then focused on to the sensitive cells of the retina.

Some squids have gone even further towards the complex eye; the lens-like skin is covered by another transparent skin that acts as a protective covering. The eye has acquired a cornea, an internal lens, and a retina.

This type of eye is common in invertebrate animals, and is often adapted and modified in many ways. It provides an adequate mechanism for creatures that do not possess a brain; and further development of the mechanism of the eye would probably be of little value to creatures that are so limited in their reflective powers. It is doubtful if the power of sight conveys any real 'meaning' to invertebrate animals in the sense that it does to human beings. The sense of vision appears to stimulate automatic responses that are essential to the animal's survival.

The possession of a skull and backbone, with a brain and spinal cord, has enabled vertebrates to make wonderful use of the power of sight. Pictures relayed from the eyes are considered by the vertebrate brain in terms of what the animal has seen before; the sense of sight provides stimuli that can be received by the central clearing house of the brain along with the other stimuli passing in from

all parts of the animal's body. And it is in the vertebrate world that the eye has developed into a sense organ of extraordinary refinement and complexity.

The form of the eye in all vertebrate animals is basically the same as that of the human eye, with modifications introduced to meet individual requirements. Light enters the eye through a transparent outer tissue, the cornea, which is generally curved and highly polished. The curved surface of the cornea begins the bending of the light, which is controlled and focused by a separate adjustable lens. The amount of light that enters the lens is limited by a muscular tissue, the iris, which alters the size of the hole in its centre to meet changing light conditions. And when the light has passed through the lens it comes to a focus on the light-sensitive cells that line the back of the eye, forming the retina.

The detailed organization of these sections of the vertebrate eye varies greatly between one type of animal and another. Fishes, for example, living in water, are unable to use the cornea to begin focusing the light that enters the eye. Light rays travel through water at almost the same speed as they travel through the watery tissue of the cornea; there is little change in direction when they leave the water to enter the cornea. In the eye of the land animal, and in human beings, there is an appreciable difference in the speed with which light travels through the air and through the tissue of the cornea; bending and focusing therefore begin at the surface of the cornea and the light is finally adjusted to focus on the retina by changing the shape of the lens.

The outer surface of the cornea in land animals is typically curved; the cornea of a fish's eye is usually flat and acts merely as a window through which the light passes into the lens. When a human being is swimming under water the cornea of the eye no longer helps in focusing the rays. Most people see poorly under water; but short-sighted people, whose eyes are normally bending light

rays too much, often see better under water than they do on land.

When animals crawled from the sea on to the land Nature had to make arrangements for protecting and cleaning the cornea of their eyes. Human beings have been provided with eyelids which can smear liquid from the tear glands over the cornea and protect the tissue from external damage. Fishes have no need of such devices. There is no danger of their cornea surfaces drying up, and incidental damage to the tissues does not have any serious effect on sight. Fishes cannot close their eyes—they have nothing to close them with. The brain of a fish is continually receiving messages from its eyes. But it does not have to act on what it sees any more than human beings act on what they 'hear' when they are asleep. If fishes sleep, as some biologists maintain, they must switch off their sense of sight at a late stage in the relay system.

Reptiles, lacking any covering of hair and coated with a scaly skin, have been unable to provide themselves with eyelids in the human sense. So they have done the next best thing, covering their eyes with a layer of transparent skin. Even with their eyes shut reptiles can see something of what is going on outside. The skin absorbs the scratches and wear that would otherwise damage the cornea surfaces. Snakes, handicapped by the lack of any sort of limb with which to rub away foreign matter from their eyes, have adopted the transparent-skin technique wholeheartedly and keep the skin as permanent windows over their eyes. As snakes wriggle along, brushing against stones and sand, the transparent covering is scratched. But a new one is provided every time the animal sheds its skin.

Most vertebrate animals control the amount of light that enters the eye with the help of an iris. As in the human eye, the iris is adjustable, enabling the animal to cope with varying daylight conditions. Fishes, however, cannot alter the size of their pupils by opening or closing the irises in their eyes. The brightness of light is steady

in a typical marine environment, and a fish can manage without elaborate equipment for meeting extreme changes in light conditions.

On land, things are very different. Most vertebrates live to a rhythm of night and day, and their eyes are subjected to all manner of reflected lights. The irises are adjustable, often over a wide range; the pupil is commonly enlarged at night and closed down during the day.

Owls can expand their irises until the pupils appear to fill the entire front of the eyes; at night the owl can detect even the feeblest glimmer of light reflected by the body of its scurrying prey. Cats and dogs can open their pupils wide at night and close them to narrow slits during the day. The slit pupil cuts off much of the available light and so restricts the sensitiveness of the animal's sight in daylight. But the pin-hole effect helps the animal to increase the definition of the image thrown on to its retina. Many animals have adopted the slit pupil in preference to the circular one used by man. Some slits are horizontal and others vertical. Snakes can close their slit pupils completely, cutting off the light when they want to rest.

In the human eye, light is focused on the retina by adjusting the curvature of the lens surfaces. The elastic tissue of the lens is stretched by muscular action when the eye is looking at distant objects; it is allowed to contract so that its curvature increases when a near object is being focused. This system has its limitations, and other vertebrate animals have developed different focusing devices. Fishes, for example, use an almost spherical lens, like a small glass marble. Instead of altering the curvature of the lens surface to focus on the retina they move the lens backward or forward inside the eye.

Some fishes keep their eye-lenses normally in such a position that they are focusing on objects only a few inches away. To see anything at a distance they have to pull the lenses back. Most animals prefer to focus their 'resting'

eyes on distant objects, adjusting them to take in nearer things as the need arises.

This to and fro movement of the lens is used by snakes and frogs as well as fishes. But most of the vertebrate animals living on land have adopted a system of lens-adjustment similar to that used by man.

Although we can adjust the curvature of our eye-lenses to give us a great range of vision, we are restricted by the elasticity of the lens tissue. We exert a muscular pull on the eye-lens when we want to flatten its surfaces, and so give good long-distance vision. But we have to rely on the natural elasticity of the lens tissue to contract the lens when we are looking at something close to our eyes. If the tissue will not contract far enough we have no way of imposing any further contraction upon it.

This reliance upon the natural elasticity of the lens is common to mammals and restricts their powers of close vision. A human infant one year old is at the peak of its ability to look at things close-to; it can examine objects about three inches from its eyes. But with increasing age the minimum distance for close inspection becomes greater as the elastic-recuperation power of the eye lenses becomes feebler. Eventually the aging human being has to provide himself with spectacles to converge the light-rays that his eye lenses cannot bring together.

Many creatures depend for their lives upon their ability to catch small, fast-moving insects. They must be able to see their tiny prey clearly over a great range of distances. And they cannot afford to depend on the natural elasticity of the eye-lens to do their focusing for them. They have therefore devised a system of bringing positive pressure to bear on their eye-lenses, increasing the curvature of the lens surfaces.

Birds and lizards adjust the soft lenses of their eyes in this way. They can squash their lenses until they are bulging through the pupils, enabling them to see the detailed outline of the tiniest gnat an inch in front of their eyes.

These variations and refinements in the light-controlling sections of the typical animal eye are matched by modifications in the retina. Vertebrate animals appear to form the retinas of their eyes from the two types of light-sensitive cell that are found in human eyes. There are rod cells, extremely sensitive to light, which look after the dim shades of twilight and darkness. And there are cone cells, responsible for daylight vision, which assess the fine details picked out by the bright light of day and may distinguish between the wave-lengths of reflected light that human beings recognize as colours. The proportion of rods to cones and the distribution of the cells on the retina vary from one species of animal to another. The retina is organized in such a way as to serve its owner to best advantage.

Many fishes have developed excellent sight by packing the retinas of their eyes with very small sensitive cells. Fishes that live in the darkness of the deep sea have retained the power of sight, even though there is no daylight in their world. They depend entirely upon the light generated in the luminous glands of their neighbours.

In order to pick up the feeble rays of this living light deep-sea fishes have eyes that often occupy most of the room in their head. Everything has been sacrificed to the essential task of detecting the feeble light of their deep-sea world. The retinas of the enormous eyes are lined with sensitive cells packed so tight that an area as big as a rice-grain contains as many cells as the entire retina of a human eye. With the help of these ultra-sensitive eyes the deep-sea fish can detect the faintest glimmer of light from other creatures in the vicinity; but it has lost its ability to distinguish details of form or colour. Neither are necessary in the surroundings in which a deep-sea fish lives.

On land, many mammals have learned to rely on their sense of smell as a guide to their environment. Sight plays a less important role than it does in the lives of fishes or of other land animals such as birds and reptiles. The eyes of mammals, including human beings, are relatively small; an

owl, insignificant in size compared with a man, has a bigger eye than a human being.

Those animals that prowl by night, like the owl or the cat, have retinas that are built up predominantly from rod cells. These sensitive cells can detect light too faint for the cone cells that cope with the bright lights of day. Some animals have retinas containing nothing but rods. These nocturnal animals live in a twilight world that is painted in patterns of varying shades of grey. The rabbit increases the sensitivity of its rod-lined eyes by having many of the individual rod cells connected to a single nerve fibre. This diminishes still further the animal's ability to resolve the detail of what it sees. But it ensures that the eye picks up even the feeblest ray of light.

Many nocturnal animals increase the light-collecting power of their eyes by lining their retinas with reflecting cells. The green eyes of a cat or dog seen in a headlight beam are reflecting the light from this special layer of cells, the tapetum.

Animals that need to see in daylight and in darkness as well are often equipped with a tapetum behind the retina of the eye. Like human beings, these versatile animals construct their retinas from a mixture of cones and rods. At night their eyes are not as sensitive as those of animals with pure-rod retinas, but the tapetum compensates by reflecting light to and fro among the sensitive cells, so that the chances of detection are increased. This scattering of light by the tapetum tends to fog the detailed accuracy of the daytime eye, so that the tapetum is not usually found in the eyes of animals which depend on acute daylight vision. The cat, for example, is equipped with a tapetum that enables it to see well in the dark; but a human being sees six times as well as a cat during the day.

Most birds are day animals, and their eyes are enormous relative to the size of the head. Hawks can see the slightest movement of a tiny animal far below them in the grass;

the cone-packed region of the retina of such birds is more sensitive than the corresponding region of the human eye. Birds have developed a sense of vision that enables them to see with greater precision than any other living creature. Sight is the dominant sense of most birds; it is the sense that helps them to catch the tiny darting insects that so often form their diet.

The eyes of birds are often backed by pure-cone retinas, with direct nerve-links between individual cells or groups of two or three and the brain. This makes for superb definition of the scene, but means that birds are virtually helpless in the dark. The European ground squirrel, an animal that is active during the day, has a pure-cone retina like a bird, with only a few cells at a time collaborating to send their messages along the same nerve fibre. Like a day bird, the squirrel can see nothing in twilight or in the dim reflections of the night. It does not have the rod cells that are sensitive to these feeble lights.

Nocturnal animals, equipped with rod-cell retinas, are generally unable to distinguish between one wave-length of light and another. This is the job that is done by cone cells, enabling human beings to see their surroundings in terms of colour. But even the possession of ample cone cells does not necessarily endow an animal with a sense of colour. The red squirrel, with pure-cone retinas, has only a rudimentary feeling for colour.

True colour vision appears to be commonest in those creatures which make use of colour in their everyday lives. Insects use colour for camouflage; birds and fishes use it in the same way, and in courting. During the breeding season male fishes will attack a piece of wood that is painted with the colour they adopt when courting.

Some creatures are provided with cone cells in their retinas which are sensitive to light of different wavelengths. The eyes of a cat, for example, are stimulated in different ways by lights of varying colour. Yet it has been proved repeatedly that the cat is colour-blind and does

not appear to 'see' the light of different wave-lengths that is stimulating its colour-sensitive cells. It has the colour equipment, but does not use it in the way that human beings do. The bull lives similarly in a world of varying shades of grey. A red rag has no more significance to a bull than a blue or yellow one; it is the movement of a fluttering cloak that irritates the animal.

When animals live by hunting they are provided by Nature with eyes that co-operate in focusing on their prey. Like human beings, they have eyes which are placed well forward on the head; the animal has stereoscopic vision and can judge the distance of any object on which its eyes are focused. The owl, which catches other animals for its food, has eyes that stare ahead of it as it searches for its prey.

Animals which are hunted, on the other hand, find that all-round scanning is more valuable to them than stereoscopic vision. The pigeon and the sparrow, the rabbit and the mouse, all carry their eyes on the side of the head. They can see what is happening on both sides of the body; a hare can see all round it without moving its head.

Many birds have combined the two techniques. The eyes of a swallow, for example, are sited in such a way that they can focus together on an object immediately ahead and at the same time keep a watch on the world on both sides of the body. These dual-purpose eyes are often lined with retinas carrying two special sensitive areas; one is concerned with the stereoscopic vision seen in the overlapping field of view from each eye; the other detects the images collected by each eye independently as it scans the scene on either side.

12

Special Eyes for Insects

Most animals have been content to model their eyes on the pattern typified by the human eye. But not so the insects. Insects have developed an entirely novel sort of eye to meet their own particular needs.

Insects are frustrated creatures; they are condemned to smallness by the respiratory technique they have adopted. Insects do not equip themselves with all the lungs and other impedimenta of a respiratory system that can carry oxygen to far-distant tissues of the body. Air needed by the living cells of the insect body is provided by a system of tubes that carry oxygen direct from air to tissues. This simple technique has many advantages to the insect; but it suffers the grave defect of being unsuitable when the insect body exceeds a certain size.

Insects have been unable to develop into big animals. The largest are only six or seven inches long; the majority are tiny creatures only a fraction of an inch in length. And they are much too small to make good use of the normal type of animal eye.

The single-lens eye gives excellent results so long as it is a reasonable size. But when it is made in miniature the iris is so small that it cannot admit sufficient light to provide a well-defined image. In the animal world the shrew is the smallest creature with a normal single-lens eye; its eye is only one-twenty-fifth of an inch in diameter, and it is so small that it is of little practical use to its owner. The shrew is virtually blind.

To overcome these deficiencies in the midget single-lens type of eye insects have evolved a radically different technique of seeing. The visual organ is a compound eye that does not provide the insect with any real image in the sense that the normal eye does. It picks up a pattern of 'samples' of brightness from various points of the scene around the insect and combines them into a mosaic that forms a fuzzy picture of the scene. This mosaic pattern takes the place of the clear-cut image that is thrown on the retina of the normal eye. It does not give the insect an actual replica of the scene before it; but it serves the insect admirably in ways that the normal type of eye could not.

The compound eye of an insect is built up from hundreds or even thousands of tiny lenses, which are packed alongside each other, forming the curved outer surface of the eye. Behind each lens is a tube that narrows towards the inside of the eye, forming a long, thin cone with the lens as base on the outer surface of the eye. At the narrow end of the cone, deep inside the eye, are sensitive cells that detect the light passing through the lens.

As the insect surveys the world around it each individual lens unit is aimed towards a definite point of the scene. The light that enters the lens is passed on towards the sensitive cells at the base of the narrowing tube. But a diaphragm fitted part way down the tube allows only a thin ray of light to reach the sensitive cells. Each unit detects the light that travels as a narrow pencil of rays down the central axis of the tube.

What the insect sees, therefore, is not a pattern of light made up from a continuous scanning of the scene, but samples of light picked up from the direction to which the central axis of each lens unit is pointing. The composite picture on the retina cells is constructed from stimuli that are put together like dots of varying brightness. The dot-mosaic that is formed is similar to that which prints a

picture in a newspaper. Seen through a magnifying glass, the latter consists of innumerable tiny dots of varying size and closeness. Each dot represents the 'darkness' of that particular pin-point area of the scene; taken together, the dots merge into a picture that reproduces the shades of light and dark of the scene as a whole.

This sort of eye can work comparatively efficiently even in the smallest insect sizes. It equips insects only one-hundredth of an inch long with the power of sight. There are no complex adjustable gadgets in the compound eye like those that operate in the eye of a bird or a fish. The insect's eye resemble a battery of carefully directed light-detecting cells that are aimed at different points of the scene.

The amount of detail that an insect sees is limited by the number and size of the lens units in its eyes. In general the compound eye cannot respond to the finer details of a scene in the way a vertebrate eye does. The vertebrate eye receives its stimuli from the entire scene before it; the compound eye can only detect the brightness of the patches of the scene towards which its units are aimed. The fruit-fly, with its tiny compound eyes, can distinguish only about one-thousandth of the detail that is distinguished by a human eye; even the honey-bee, which is a comparatively large insect, is only one-hundredth as efficient in this respect as a human eye.

There is a wide variety of behaviour in the insect world; some insects, like the praying mantis and the dragonfly, are hunters; others, like the grasshopper and the cricket, are vegetarians. The compound eye is adapted by each species of insect to suit its own particular needs. Dragonflies cram so many lens units into their eyes that there is little room left on the surface of the head for anything but eye. The eyes form bulging domes that meet in the middle of the insect's head, giving the dragonfly a field of view that extends all round its body. Some of the lens units in each eye point towards the same direction, so

that the dragonfly has true stereoscopic vision. It can follow the intricate movements of the gnat it is chasing, estimating accurately how far its quarry is away.

Vegetarian insects have no need of such accurate vision; their food cannot move away when it is being attacked. The compound eyes of insects like the grasshopper are smaller than those of hunting insects and are sited towards the sides of the head. The grasshopper has no stereoscopic vision; it is like the pigeon, which uses each eye to watch what happens on either side. Much of the grasshopper's head is occupied by chewing equipment; this is much more useful than an over-developed eye, which would merely take up valuable space.

The sensitivity of the insect's compound eye diminishes rapidly with increasing distance. The further away an object is, the fewer lens units it can stimulate. Most insects behave like near-sighted human beings, seeing things in detail only when they are immediately in front of their eyes.

Movement attracts an insect's attention much more than a mere variation in the depth of light and shade. Bees will be attracted towards a group of fluttering flowers much more than towards a similar patch of flowers sheltered from the breeze. Movement of the petals stimulates adjacent lens units in the eye, so that the insect's attention is drawn towards the flowers.

The single-lens eye of human beings is remarkably efficient in its ability to detect differences of brightness. The light reflected from the dim outlines seen on a dark night is only one-thousand-millionth of the light that reaches the eye on a bright midsummer day. Yet so versatile is the human eye that it can cope with variations in brightness over this immense range.

The insect's compound eye is much less adaptable. An insect will think that night has come when the light falls to only one-hundredth of the brightness of a summer day. A thundercloud shutting off the sun will send the insect

world to sleep; a bee captured in a tin becomes quite drowsy in a minute or two.

This poor sensitivity to degrees of light and shade has limited the use of compound eyes in the insect world. Night-flying insects tend to rely on a sense of smell rather than on vision. Some insects, like the praying mantis, can adjust the diaphragm in their lens tubes so that more light reaches the sensitive cells at night. This restricts the detailed accuracy of the insect's vision, but allows its eyes to detect much fainter light than they otherwise could.

Although insects live in a world so deficient in degrees of light and shade, they add to the attractiveness of their surroundings by distinguishing different colours. Experiments with bees have proved that these insects can detect light of different wave-lengths just as human beings do. But the bee's colour range is not the same as ours. It cannot see the deepest shades of red at one end of our spectrum. But it makes up for this by extending its range of visibility at the other end of the spectrum; a bee can see ultra-violet light as a colour. The wave-lengths of light in the bee's colour range fall into four groups, each of which the insect recognizes as a definite colour. A bee can distinguish between ultra-violet, blue plus violet, blue-green, and yellow plus green. These are the four true colours of the insect.

Until recently it was believed that insects could not respond to variations in the wave-length of light within these colour ranges; blue, for example, looked the same as violet to the bee. But research has now shown that the bee can respond to shade-variations, distinguishing between light of different wave-lengths in the same colour group. Even so the world must be a drab place to the insect, with a severely limited sense of colour values. Its compound eye cannot give it the versatility that the human eye bestows upon its owner; human beings can distinguish more than 17,000 gradations in the colours of the world around.

This four-colour world enjoyed by bees is not necessarily the same as that in which other insects live. White butterflies can distinguish between four ranges of wave-lengths, but the ranges are not the same as those seen by the bee. Colours which a bee can separate as yellow and blue may both look identical to a butterfly. Deep red, which is invisible to a bee, can be a particularly attractive colour to a butterfly in search of food. The firefly communicates with its mate by flashing a light that is often rich in long-wave red.

This colour vision of insects is not confined to the bright light of day, as it is in the case of vertebrate animals. Insects can distinguish their different colours even in twilight.

Bees use their sense of colour to identify flowers on which they are working. Blue is the bee's favourite colour, and blue flowers can be certain of attention from the bee. When a bee is 'working' a patch of flowers it will remember the colour of the flowers and return repeatedly to them from the hive. Experiments have shown that bees can be trained to select any colour from their visible spectrum, including the wave-lengths we call ultra-violet.

The compound eye has given insects like the bee a visual organ that can operate with reasonable efficiency in small sizes. But this type of eye has been adopted throughout the insect world, even by large insects which could well have equipped themselves with a single-lens type of eye. This preference for the compound eye, with its indifferent image-forming power, is not so illogical as might be supposed. The compound eye can serve its owner in a way that the ordinary eye will not. It can be used to provide the insect with a remarkably efficient direction-finding system.

Much of our knowledge of the way in which insects orientate themselves with the help of light has come from work carried out by Professor Karl von Frisch, of the University of Graz. Since the 1920's, Professor Frisch has

been studying the behaviour of bees and has discovered how these insects pass on information about the location of food-supplies from one individual to another.

When a bee has found a rich supply of nectar during a foraging expedition she returns to the hive determined to tell her good news to the other bees. This she does by dancing on the surface of a comb. If the source of nectar, or pollen, is within about a hundred yards of the hive the bee performs a Round Dance; she follows a circular path backward and forward as though making a figure of eight movement with the two loops superimposed one on top of the other. The other bees, seeing this dance, know that the nectar is near the hive; they pick up samples from the stores the bee has carried in and set out post-haste to search for the scent that will lead them to the rich store discovered by the dancing bee.

But if the nectar is more than about 100 yards from the hive the dancing bee provides more detailed information about its location. The pattern of its dance changes, so that the bee follows a true figure of eight path formed from two half-circles with a straight side joining each. This figure of eight dance is carried out with remarkable precision. And as the other insects watch they can tell from the dance how far away the nectar is from the hive and the direction in which it lies.

As the bee dances along the straight path between the two loops of her dance, she waggles her abdomen; this type of dance has become known as the waggle dance. The vigour with which the bee carries out its dance depends on the amount of nectar that is available in the store it has discovered. A lot of nectar stimulates a rapid dance; a small supply is indicated by a slow dance. As the other bees watch they can assess the amount of effort that will have to be put into the job of collecting the nectar. They break up into gangs big enough to deal with the food that is available in stores that have been discovered by different bees.

As bees will often feed at distances of two miles or more from their hive, they must be able to indicate accurately where the nectar is to be found. This they do as they perform the waggle dance, which tells other bees the distance of the nectar from the hive and also the direction in which they must fly. The speed with which the bee makes its loops in the dance depends upon the distance of its nectar discovery from the hive. When the feeding place is only 100 yards away the bee makes about ten circuits in a quarter of a minute. If the nectar is nearly two miles away the dance slows down to three circuits in the same time. As the other bees watch they can apparently 'remember' the distance indicated in this way by the dancing bee.

With the distance from the hive fixed, the bees still have to know the direction in which to fly if they are to find the nectar. And von Frisch found that the dancing bee indicates the distance by adjusting the slope of the straight path in its dance; the angle formed by the straight path and the vertical corresponds to the angle between the direction of the nectar and the sun. The bee, in other words, takes a bearing on the sun and then passes this information to its colleagues.

When the nectar lies in the direction of the sun itself, as judged from the hive, the straight path of the waggle dance is vertical on the face of the comb, with the bee dancing upward as it passes between the loops of the dance. If the nectar is in the direction opposite to the sun the straight path is again vertical, but the bee dances downward along it. When the nectar is at an angle to the direction of the sun this angle is the same as that between the vertical and the straight path followed by the bee.

During the day, as the direction of the sun changes, the dancing bees adjust the angle of their waggle dance accordingly. If a bee is caught far from the hive, and then released, it will make its way unerringly to the hive. If it is kept in the dark for an hour or two it will set off in the same direction relative to the sun, and lose its way; the

sun has changed its position during the bee's captivity, but the bee has remembered the angle as it was when it was captured.

Inside the hive the bees perform their direction-indicating dance on the vertical surface of the comb. They substitute the force of gravity for the light of the sun; a vertical line is identified as the direction of the sun. But if they are made to dance on a horizontal platform they can still pass on directions to the other bees, using the sun directly as their fixed point. If the nectar is in the direction of the sun they dance towards the sun as they mark out the straight path in the figure of eight.

Von Frisch tried to baffle his bees by letting them dance on a platform that could be rotated. But the bees adjusted the angle of their dance as the platform was revolved, keeping the appropriate angle with the sun.

When the direction-finding system was first discovered it seemed so fantastic that it could not possibly be true. But von Frisch himself and other research workers have now confirmed that it is used as a matter of course by bees and other insects. The more it is studied, the more astonishing does the whole technique become.

Von Frisch carried out experiments with bees inside glass-topped hives. Under these conditions the bees had no need to make use of gravity as a substitute for the sun. They performed their dance on horizontal surfaces, giving the flight instructions directly by reference to the sun. But the most astounding discovery of all was that the bees did not even have to see the sun to take their direction from it. They could manage just as well by looking at any convenient patch of blue sky. Somehow or other they could use this light to indicate the position occupied by the sun that lay hidden behind the clouds. And they could orientate themselves with respect to the unseen sun.

Professor von Frisch found that he could upset the orientation of the bees by reflecting light from a patch of sky into the hive. When it was reflected to enter at an

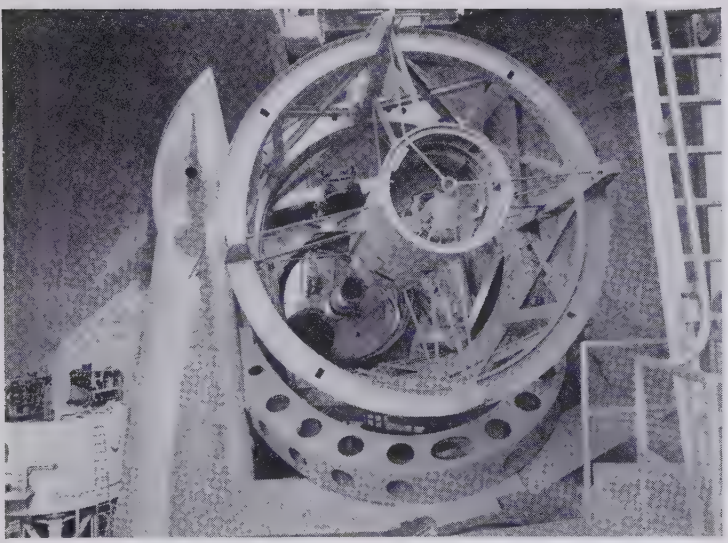


Photo Mount Wilson and Palomar Observatories

THE "GIANT EYE" OF PALOMAR

This picture shows an observer sitting in the prime-focus cage of the Hale Telescope, largest telescope in the world. The 200-inch mirror can be seen deeper inside the huge steel cradle.

Photo High Altitude Observatory, Boulder, Colorado

A HYDROGEN CLOUD

The great cloud of hydrogen gas has formed an arch 200,000 miles high above the surface of the sun. Photographed on June 4, 1946.

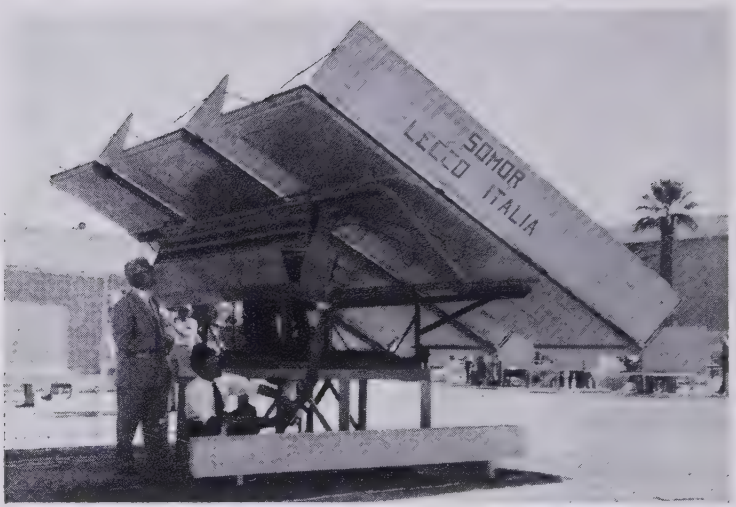


Photo Societa Motori Recuperi

THE SOMOR $2\frac{1}{2}$ H.P. ENGINE

Sulphur dioxide is vaporized in the flat-plate sunshine-collector of this engine, providing sufficient power to operate a water pump.

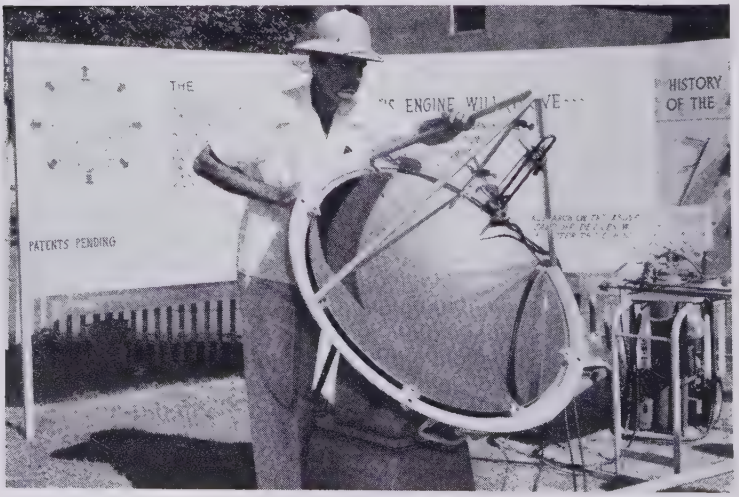


Photo William A. Rhodes and Harrison E. Lang

THE NOVOID ENGINE

The sun's rays are concentrated on to a column of liquid which alternately explodes into a burst of high-pressure steam and condenses again. The engine produces rapid pulses of mechanized energy in this way.

angle of ninety degrees to the proper direction the bees were ninety degrees out in their direction-finding system.

Experiments of this sort confirmed that bees could distinguish in this way between the different types of light coming from different positions in the sky. And the insects could relate the quality of light to the position of the sun in the sky. The most reasonable explanation of this phenomenon was that bees could detect the polarization of light.

When sunlight is passing through the atmosphere its rays are scattered by the particles and droplets in the air. One of the effects of scattering is to polarize the light, which reaches the ground with its waves vibrating predominantly in definite planes.

The degree to which light is polarized and the direction in which the waves vibrate are different in different parts of the sky relative to the position of the sun. By understanding and measuring the polarization of light from any patch of sky the bee can pin-point the position of the hidden sun.

This explanation of the bee's direction-finding system has been confirmed by submitting bees to the effects of polarized light. A transparent material, Polaroid, will transmit light preferentially with a single direction of polarization; it cuts off waves that are vibrating in other planes. When a sheet of Polaroid is placed above a transparent hive the bees will orientate their dance in a direction controlled by the polarized light. If the glass is rotated so that the plane of vibration of the waves is altered the bees will change the direction of their dancing pattern too.

There is now no doubt that the compound eyes of bees can assess the direction in which light waves are vibrating. Moreover, bees can remember the plane of vibration and use it to determine the direction in which they fly.

Other insects are known to be able to find their way about by using their eyes to detect polarization differences in this way. Experiments carried out at Oxford have shown that ants can make their way over rough ground with

unerring accuracy towards their nest. They know the direction in which it lies by following the route laid down by the polarization 'compass' in their eyes.

In 1950 Dr T. H. Waterman, of the Osborn Zoological Laboratory, carried out experiments which showed conclusively that compound eyes could distinguish between rays of light vibrating in different planes. The compound eye is a characteristic of crustacea as well as insects, and there is a crab, Limulus, with a primitive compound eye that is especially suitable for research. The eye of a bee, with thousands of lens units, is difficult to dissect and study in detail; but the eye of Limulus contains only 300 separate units, each of which can be studied individually with the help of modern techniques.

At the eye-tube base in Limulus, there are fourteen to sixteen sensitive cells, each connected through its own fibre with the optic nerve. By dissecting the optic nerve it is possible to separate the fibres and identify each one with the sensitive cell that it serves.

When an individual light-sensitive cell in one of the visual units of Limulus's eye is stimulated with a fine pencil of light there is an immediate impulse through the nerve fibre connected to the cell. If the light continues to shine a succession of impulses goes on travelling along the fibre as though to remind the optic centre that the light is still there. The brighter the light, the more frequent are the impulses.

The experiments carried out by Dr Waterman showed that these nerve impulses caused by light could be varied by altering the plane in which the light was vibrating. A sheet of polarizing glass placed between the light source and the visual cell allowed only light vibrating in a certain plane to pass. When the glass was rotated the plane of the light-vibrations was rotated too. And the frequency of the impulses sent through the nerve fibre from the cell on which the light was shining rose and fell to maximum and minimum values depending on the position of the

polarizing screen. In two positions of the screen, 180 degrees apart, the nerve impulses were at a maximum; but in the two positions at right angles to these the impulses were at a minimum. The visual cell was apparently stimulated more intensely by light vibrating in one direction than by light vibrating at ninety degrees to this direction. In between these positions of maximum and minimum stimulation rotation of the polarizing screen caused a gradual increase or decrease in the frequency of the stimuli passing through the nerve fibre.

The visual cells in the compound eye of this crustacean, Limulus, are therefore able to send messages through the nerves which alter in intensity with the angle of the plane in which the light is vibrating. Limulus can undoubtedly distinguish between the unpolarized light that comes from the sky in the direction of the sun and the light that reaches a maximum degree of polarization in the sky at ninety degrees from the direction of the sun. It can also assess the various degrees of polarization in between.

It is reasonable to suppose that other crustaceans and insects are sensitive to polarization in a similar way. But it does not necessarily follow that all have learned to navigate with the help of polarized light in the way that bees and ants are known to do.

This direction-finding technique adopted by Nature has now been used by man. Instruments have been made which measure the polarization of light from any region of the sky; these instruments act as compasses for fliers in Arctic regions, where the ordinary magnetic compass is of limited use and the sun itself is not to be seen.

13

Light takes a Photograph

PHOTOGRAPHY, like the motor-car, is one of those modern marvels that nobody invented. It grew from the discoveries of many people and was made possible by combining a number of different scientific techniques. As usual, the ancient Greeks had a hand in it.

Aristotle, for example, was puzzled by the fact that sunlight passing through a small square hole would throw a round spot of light on the ground. He noticed also that when the sun was partially eclipsed the light was crescent-shaped, even though it had passed through an angular hole. It appeared that the sun itself, and not the hole, was controlling the shape of the 'image' that fell as a spot of light upon the ground.

By the eleventh century A.D., when the great Islamic scientist Alhazen wrote his Book of Optics, this phenomenon had been studied and put to practical use. It formed the basis of an optical device known as the camera obscura. This was the fore-runner of the modern camera.

The camera obscura was simply a box with a tiny hole pierced in one wall. Light entering the hole threw an image of the scene in front of the hole on to the opposite wall of the box. This picture of the scene was upside-down; it could be viewed either by looking through a special opening in the top of the box or by making the 'screen' from transparent paper or glass so that the picture could be seen from outside.

Many early scientists experimented with the camera

obscura. Often it took the form of a darkened room with a small hole allowing light from outside to fall upon a screen. The screen would show a picture, upside-down, of the scene outside.

By the beginning of the eighteenth century portable camera obscuras were being manufactured; they were used by artists to provide a picture of the scene they were sketching. These camera obscuras were similar in principle to the simple box camera we use to-day. Light entered through a pin-hole and threw an image on the opposite wall of the box. But they differed from the photographic camera in that they could not capture the image and record it permanently as a picture. They were 'cameras' that could not take a photograph; all they could do was to throw the image of the scene on a transparent paper or ground-glass screen. To preserve the image in the form of a photograph, something was needed which would react to different intensities of light. By allowing the pattern of light of a camera image to fall on a surface carrying a light-sensitive substance of this sort a record would be left of the brightness in each infinitesimal area of the image. If this record could be made permanent in some way the camera obscura would be able to capture a lasting picture of the scene that lay before it.

During the sixteenth century Leonardo da Vinci made accurate drawings of a camera obscura. But he could not suggest how the image it threw might be preserved. Shortly after his death it was found that certain salts containing silver would darken on exposure. Had Leonardo da Vinci lived to learn of this, his genius might have led him to relate the phenomenon of the camera obscura to the darkening of silver salts; he could well have developed the first photographic camera.

It was not until 1727 that a German chemist, J. H. Schulze, discovered that the darkening of these silver salts was caused by light. Schulze covered a layer of the salts with a stencilled card and exposed the card to light; he

found that the salts were darkened where the light fell through the letters stencilled on the card.

Throughout the eighteenth century scientists studied these changes caused by light falling on certain chemicals. Pictures were transferred to paper and other materials impregnated with light-sensitive silver salts. But there was no way in which the patterns or pictures formed could be made permanent. Once they were brought into the light the entire surface was affected and the picture disappeared.

During the early nineteenth century Nicéphore Niepce, a French printer, discovered a novel way of making light leave a record of a picture or design. Niepce found that light falling on a layer of bitumen would make it insoluble in its usual solvents. When a sheet of bitumen-coated glass was exposed in a camera obscura the bright areas of the image hardened the bitumen, but the darker areas left it unaffected. When the glass was washed with solvent after exposure a picture remained in the form of insoluble bitumen on the glass.

By 1822 Niepce had perfected this process and the first permanent photograph had been made. Niepce called his process heliography.

Meanwhile a painter called Daguerre had been experimenting with light-sensitive silver salts. In 1829 Daguerre joined forces with Niepce and a new photographic process was developed. The picture in the camera obscura was allowed to fall on a silver plate that had been exposed to iodine vapour. Light affected the surface of the plate in such a way that a permanent image was formed when the plate was held in mercury vapour after exposure.

This was the Daguerrotype process which was widely used just over a century ago. It was a cumbersome technique and needed great skill to operate it. At first exposures lasted for several minutes, but were later reduced to a few seconds.

Meanwhile, in England, Fox Talbot was carrying out the

experiments which were to lead to photography as we know it to-day. Fox Talbot found that paper impregnated with silver chloride could capture the image in a camera obscura, the silver salt darkening where the light fell on it. By treating the exposed paper with other chemicals Fox Talbot was able to destroy its light-sensitiveness and make the image permanent.

This 'Calotype' process was the real fore-runner to modern photography. The picture obtained in the camera reproduced the pattern of light and shade of the image in the form of a 'reversed' picture; where light was brightest the sensitive paper was darkest, and where the image was dark the paper remained light. The picture as it came from the camera was what we now call a 'negative.'

Fox Talbot made his negatives transparent by oiling the paper. Then he used a negative as a stencil, putting it on top of another sensitive paper and exposing it once again to the light. Wherever the negative was dark, the sensitive paper underneath was shielded from the light and remained white; but where the negative was light, the paper underneath was darkened. So, from the negative, Fox Talbot was able to make a 'positive' print which reproduced the shades of light and dark that formed the original image.

This Calotype process was described by Fox Talbot to the Royal Society in London on January 30, 1839. The principles on which it was based are essentially the same as those which underlie our modern photographic industry. Great advances have been made in photography during the last hundred years. These have largely been improvements and refinements rather than fundamental changes in the process developed by Fox Talbot.

To-day we still use light-sensitive silver salts to record the image that falls on the back of the camera. These salts are spread as an 'emulsion' in a layer of gelatin that is held on a support of glass or plastic film. As light enters the camera it throws an image on the sensitive emulsion;

where the light is brightest it darkens the silver salts the most, and vice versa.

The film from our modern camera gives us a negative with the light and shade wrong way round, just as Fox Talbot's Calotype process did. And we reverse it once again by using the negative as a stencil over a light-sensitive printing paper; the light areas allow light through to darken the silver salts in the printing paper, so that the positive print has the light and shade the same way round as in the original scene.

In a modern plate or film the light-sensitive silver salts are held in the form of tiny crystals in the gelatin coating. These crystals may be one-twenty-five-thousandth to one-two-hundred-and-fifty-thousandth of an inch in diameter, the size depending on the type of film. A square inch of film will contain up to a million million individual crystals packed together so that each one is separated from its neighbours by only about a crystal width. The layer of gelatin carrying a silver-salt crystal is itself less than one-thousandth of an inch thick, yet the crystals may pack forty-deep into the gelatin layer.

When light strikes these tiny crystals, or 'grains,' of silver salt it frees atoms of silver from the chlorine, bromine, or iodine atoms with which they are associated. If light shines long enough a crystal will darken as the opaque, metallic silver is formed. The different degrees of light and shade that record a picture in a photographic film are due to silver that is released from the crystals of silver salt inside the emulsion. Subsequent treatment of the exposed film removes the unaffected silver salt, leaving transparent areas in the negative where little light has struck the film.

In the early days of photography the sensitive paper was exposed until the pattern of light forming the image had made a corresponding pattern on the layer of silver salts. Exposures had to be prolonged to enable the crystals to release their silver where the light was striking them.

But Fox Talbot made a discovery that shortened the exposure time needed to record the image and made possible our modern short-exposure photography.

Fox Talbot found that it was not necessary to expose the sensitive layer to light until the crystals have set free their silver. A short exposure in the camera did not leave a visible picture on the emulsion layer; but in some strange way the light-struck crystals were left in a sensitive state. They registered the fact that light had struck them with a definite intensity. And even though the light itself was insufficient to liberate silver from the crystals, it left the crystals in a state where they could release their silver easily by subsequent chemical treatment.

Fox Talbot had discovered what we now know as the latent image effect. Instead of exposing the film long enough for the light to create an actual pattern of liberated silver in the emulsion, we expose it for only a short time. This exposure causes a 'latent image' in the emulsion. Nothing can be seen, but the crystals have acquired a pattern of sensitiveness depending on the amount of light that has struck them. The ease with which each crystal will release its silver on subsequent chemical treatment depends upon the dose of light it has received. 'Development' of the film in a suitable chemical continues the work of silver-release begun by the light. Once the latent image has been brought out in this way by development the residual unaffected crystals of silver salt are dissolved from the emulsion, leaving a finished negative.

When daylight strikes a crystal of silver salt in the sensitive emulsion most of the liberation of silver is brought about by the shorter wave-lengths of light. Ultra-violet and blue are the most effective. If an emulsion is to make a faithful record of an image, however, it must be able to translate the complete range of visible wave-lengths into terms of light and shade.

A simple silver-salt emulsion, affected only by the ultra-violet and blue waves, records the longer-wave colours—

green, yellow, orange, and red—as areas of black or dark grey. To the silver salt, these colours are not light at all. The early types of light-sensitive papers and plates could not make a faithful record of the image in terms of the varying brightness of the rays of different colours that struck it. They recorded a picture representing the variations in ultra-violet and blue light reflected from all the objects in the scene.

In 1873 H. W. Vogel, of Berlin, found that photographic plates could be made sensitive to waves of longer length by treating them with special types of dye. Intensive research followed this discovery, and dye-sensitizing has provided us with emulsions that will record all the waves in the visible spectrum and far into the infra-red region as well. Modern panchromatic films are affected by the full range of visible waves.

Nowadays photographic films are made in enormous quantities and the emulsions are modified to react to all manner of light conditions. The size of the crystals of silver-salt is controlled within fine limits. The larger the crystals, the greater is the sensitivity of the film. Light falling on a crystal will stimulate it so that development converts it all to metallic silver; the larger the crystals, the greater the result will be from a definite quantity of light. On the other hand, the smaller the crystal size, the better the definition of the picture will be. The emulsion-maker has to compromise by adjusting the crystal size to suit the different requirements of the modern photographer.

Although it is more than a hundred years since Fox Talbot discovered the latent-image effect, we still do not understand exactly how the process works. We do not know what happens in a 'light-struck' crystal of silver-salt to make it more sensitive to conversion to metallic silver. Much of the photographic research now being carried out is concerned with the latent image process.

It has been found that the gelatin used as a support for

the silver-salt crystals plays a vital role in the formation of the latent image. Gelatin is a natural protein extracted from the hide and bones of cows. We do not know its exact chemical structure. Gelatin contains several impurities in the form of chemicals that play some part in living processes of the animal. Among these impurities are sulphur compounds formed from sulphur-containing substances in some of the cow's favourite foods, like mustard. Research has shown that these sulphur compounds in natural gelatin sensitize the crystals of silver salt in the emulsion. They make the light-struck crystals more ready to decompose to silver when the exposed emulsion is developed.

Nowadays chemists can make synthetic sensitizers that will do a similar job, and photography no longer depends upon the liking of a cow for mustard.

It is believed that these sensitizing chemicals settle in the form of little particles of impurity on the surface of the silver-salt crystal. They act as collecting centres, attracting atoms of silver towards them as they are set free inside the crystal when light is falling on it. The formation of the latent image is essentially an early stage in the conversion of the light-struck crystal to silver. Collecting round the impurity spot, the small amount of silver encourages the entire crystal to liberate its silver during development.

The difficulty of proving or disproving this theory lies in the infinitesimally small amounts of silver involved in the formation of the latent image. Although a typical silver salt crystal in a film is only about one twenty-five-thousandth of an inch in diameter, it is large by comparison with the atoms it contains. A crystal of silver bromide in a modern film will be built up from as many as one thousand million atoms each of silver and bromine.

When these crystals are struck by light during a normal camera exposure only 200-300 atoms of silver are set free from their intimate association with the bromine atoms. These few hundred liberated atoms collect at the impurity spot on the surface of the crystal, and hold the crystal in

readiness for further liberation of the remaining millions of its silver atoms during development of the film.

The amount of silver involved in latent image formation is therefore incredibly small, and defies detection by ordinary means. The world's cinema industry uses thousands of millions of feet of film every year; but the weight of silver set free as latent images in the countless millions of exposures made in a year amounts to only an ounce or two.

Inside the crystal of silver bromide in a film emulsion the atoms of silver and bromine are arranged in serried ranks. The geometrical precision of a crystal is a consequence of the ordered arrangement of the atoms of which it is composed. If the latent image is in fact formed by the collecting of silver at spots on the surface of crystals it means that silver atoms must make their way to the surface specks from inside the crystal. In 1938 two scientists, R. W. Gurney and N. F. Mott, put forward a theory suggesting how this migration of silver could take place.

Inside the crystal, silver and bromine are not in the form of normal atoms. Each silver atom has given up one of the circulating electrons from its miniature solar system to a bromine atom. As the electron is a negative electric particle, the silver atom is left with a positive electric charge; it is an ion—a charged atom. Similarly, every bromine has acquired an extra negative electron and has become a negative ion. Taken together, a pair of silver and bromine atoms can be regarded as a neutral molecule of silver bromine.

If silver is to be set free from its close association with bromine in the silver bromide crystal the silver ion must be provided with an electron. This restores its atomic structure; it becomes an independent neutral atom instead of a positive ion held fast by electrical attraction to its negatively charged partner, the bromine ion.

Inside a silver bromide crystal things are seldom as well-ordered as they seem. The arrangement of the atoms tends

to come to grief in places, and the ranks are broken, forming regions of weakness. Silver ions break away from their normal positions in the crystal and can wander about among the other ions. A concentration of negative electricity will attract the positively-charged silver ions towards it; and this is what happens during latent-image formation.

When light falls on a silver bromide crystal electrons are set free from the bromide ions in the crystal; the loss of an electron converts an ion back into a bromine atom. These free electrons can move about inside the crystal, and they are attracted to a sensitivity speck on the surface. Here the electrons congregate and set up a little area of negative electric charge. The mobile silver ions in the crystal are attracted towards this electronic lure. As they reach it each atom unites with one of the electrons and is changed into a neutral silver atom. The sensitivity speck therefore becomes a collecting centre for electrically neutral, immobile silver atoms.

When a photograph is taken the light-struck crystals in the emulsion react in this way. Only a few hundred of the millions of atoms in the crystal are able to migrate to the sensitivity specks. But once there they act as a nucleus for the remaining silver ions in the crystal. When the film is developed electrons from the developing chemical are poured into the surface specks of silver on the crystals. This gives them a negative electric charge and attracts more silver ions from inside the crystal. So, the silver of the crystal is gradually accumulated at the collecting centres on the crystal surface. If development continues long enough all the silver in the crystal is set free from its bromine partner in this way. The bromine is absorbed into the developer liquid.

Under the ordinary microscope a developed crystal of silver bromide looks like a blackened form of the original crystal. But seen under the more powerful electron microscope, each crystal appears to have turned into a mass of

tangled wire. This strange formation supports the theory that silver is deposited in sensitivity specks on the crystal surface. As silver ions flow to the specks they will be deposited as neutral atoms beneath the silver already there. So each speck will produce its silver in the form of a wire that is pushed out steadily from the surface. Under the ordinary microscope the triangular or hexagonal crystal form will be retained by the gelatin in which the crystal was embedded. But in the electron microscope the silver wires can be seen.

Although this theory of latent-image formation has been accepted as a useful basis for photographic research, it is not to be regarded as the final word on how things happen. Theories never are; they merely represent the best explanation that fits the facts as known.

During the latter half of the nineteenth century many attempts were made to devise methods of taking photographs in colour. The principles by which this could be done were worked out, and simple colour photographs were taken. Clerk Maxwell, the physicist who established the theory of electromagnetic vibrations, suggested in 1861 that any colour could be reproduced by mixing the three primary colours red, green, and blue-violet. Maxwell took photographs of a piece of coloured ribbon; one photograph was taken through a red solution, a second through a green solution, and a third through a blue solution. Each of these coloured solutions transmitted only its characteristic colour of light from the mixture of light that came from the ribbon; the red solution, for example, absorbed the green and blue light and transmitted red. The picture formed on the sensitive emulsion represented the pattern of light of one particular primary colour coming from the image. The three negatives therefore provided a record of the scene in terms of three primary colours.

Clerk Maxwell made transparencies from his three negatives and projected each in light of the colour in which it was taken. Superimposed one on the other, the three

coloured images blended into one which showed a faithful reproduction of the colours of the ribbon.

Although this sort of colour photography is adequate for taking pictures of immobile objects, it is of little use for instantaneous photographs of moving things. Modern colour photography has developed to the stage where any amateur can take colour photographs in an ordinary camera. The basic principles of the processes are very much as Clerk Maxwell outlined nearly a hundred years ago. But it is only during the last twenty years that chemists have synthesized dyes and colour-forming chemicals that make simple, versatile colour photography possible. Modern colour films contain three distinct layers of light-sensitive emulsion spread one on top of another. One layer is sensitized to record the blue light in the image, one the green, and the other the red. In every part of the image the three layers analyse the light that falls upon them, recording the proportions of the three primary colours that make up that particular point of the image.

When the film is developed the silver image in each layer is changed into an image formed by a dye of appropriate colour. Light passing through each infinitesimal point of a developed transparency emerges as a mixture of the primary colour that matches the colour to which this point of the image was exposed. The picture as a whole is a colour-match of the scene.

The modern colour film is a marvel of manufacturing ingenuity and control. Altogether it may contain seven separate layers, each one only fifteen hundred-thousandths of an inch thick. The layers are spread so accurately that there is only a few millionths of an inch variation in thickness between one part of a sheet of film and another.

Side by side with this progress in colour photography there have been corresponding advances in the techniques of black and white photography. When Nicéphore Niepce made his first heliographs during the 1820's he used exposures of six hours in bright sunlight to bring about

the necessary changes in his light-sensitive material. Nowadays we can record a latent image on silver-salt emulsions with only one thousand-millionth of a second's exposure to light. This incredible sensitivity is due to the extraordinary phenomenon of latent-image formation by silver bromide and other silver salts. Many other light-sensitive materials have been discovered, in which light can bring about chemical changes, so that the substance can act as a photographic recording device. The ordinary blue-print used for engineering drawings is a picture printed by light acting on a sensitive chemical. But changes of this sort are relatively slow. Each bundle, or quantum, of light energy will act on one molecule of the sensitive substance, so that to effect a change suitable for recording an image the exposure must be prolonged. Silver salts, on the other hand, are merely 'triggered' by the light that falls on them. One quantum of light energy will start off a chemical change that results in the release of millions of silver atoms. That is why we can take pictures with exposures of only a few thousand-millionths of a second.

Progress in the development of sensitive emulsions has been accompanied by improvements in the camera itself. The principle of the camera remains essentially the same as it was in the days of the camera obscura. But, in place of the pin-hole letting in only a narrow pencil of light rays from each point-source of the scene, we now have lenses that can concentrate the light coming through large apertures. With modern lenses we can capture enough light to provide a photograph on the dullest day.

Photography has made its way into every aspect of our daily life. Thousands of millions of snapshots are taken by amateur photographers every year, and the manufacture of sensitive film has become one of the world's great industries.

Photography has enabled us to take pictures of stars in light too feeble to see with the naked eye. It records the mixture of waves that are split into their separate com-

ponents by the prism, and tells us about the elements that are present on the sun.

Photography is no longer restricted to the range of visible rays we recognize as light. Silver emulsions can now be sensitized to make them react to rays of almost any wave-length. We can take photographs in the 'light' of the shortest gamma rays and X-rays, and we can also make pictures with the help of long-wave, infra-red rays.

Fast-moving particles will leave their mark in a photographic emulsion layer, enabling us to 'see' what happens to the debris from atomic disruptions. Streams of electrons, taking the place of visible light, have given us photographs of virus particles too small to be seen through the ordinary microscope.

We have come a long way since Fox Talbot took the first photograph of a window in Lacock Abbey just over a century ago. How strange it is that we still know so little about the latent image process on which modern photography is based.

14 The Versatile Lens

In the British Museum there is a curved ornament of rock crystal that was found in the ruins of Nineveh. It is flat on one side and rounded on the other. It may well be one of the first optical instruments to have been used by man, more than 2500 years ago.

Many transparent lens-shaped ornaments of this sort have been discovered among the ruins of ancient civilizations. Their owners must have recognized that these ornaments were able to magnify things seen through them. But it is doubtful if the lenses were used for anything more than amusement.

During the first century A.D. a Roman philosopher, Lucius Annæus Seneca, explained to his students that they could look through glass flasks filled with water in order to see 'difficult things that frequently escape the eye.' So the idea of using curved lenses as an aid to human vision had certainly been established nearly 2000 years ago. It was at this time that the lens was given its name, from its resemblance in shape to a lentil (Latin, *lenticula*).

For a thousand years and more the lens as a practical optical instrument was almost forgotten. Then in 1266 Roger Bacon, a Franciscan monk who lectured in natural science at Oxford, published his book *Optics*, in which he discussed how 'crystal bodies' could be placed before the eyes to aid sight. Bacon outlined the principles of the microscope and the telescope some 300 years before these instruments were invented.

Later in the thirteenth century an Italian, Salvino D'Armate, made a pair of spectacles—probably the first ever used in the Western World. By the end of the century spectacles were being worn by many of the wealthier courtiers and landed gentry.

During the fourteenth and fifteenth centuries the science of optics made slow progress. Then, in 1591, Zacharias Janssen, the son of a Dutch spectacle-maker, made the world's first microscope. Janssen mounted two lenses in a brass tube eighteen inches long and two inches wide. He found that by looking at small objects through this simple instrument he could see them magnified to as many as nine times their normal size. The light reflected from each point of the object was bent and guided by the lenses in such a way that it created an image larger than the object itself.

Janssen and his father examined all manner of small things through their microscope. According to ancient Dutch records, they made other optical instruments, including a telescope.

Janssen's discovery of the microscope was followed up immediately by other scientists, and the instruments were modified and improved in many ways. In 1665 the English philosopher Robert Hooke published his *Micrographia*, in which he included a complete description of lens-making, refraction, and the building of microscopes. Hooke is in fact credited with the invention of the compound microscope—the forerunner of those we use to-day.

Greatest of all the pioneers in the early study of microscopy was Anton van Leeuwenhoek. Beginning in 1673, van Leeuwenhoek examined thousands of specimens through the microscope, sending detailed descriptions of what he saw to the Royal Society in London. The lenses in the simple microscopes he used were as small as an eighth of an inch in diameter, but were strongly curved. Some of van Leeuwenhoek's lenses were remarkably powerful; one was able to magnify 270 times. With these lenses van Leeuwenhoek discovered bacteria and protozoa,

yeasts, and other microscopic living things. He showed that bacteria swarmed in human saliva, and that there were tiny living organisms in water that looked clean and clear. He discovered the corpuscles in human blood.

During the seventeenth and eighteenth centuries the microscope opened up a new world to science. Peering through their instruments, philosophers were amazed at what they saw. Tiny creatures lived in a micro-world whose existence had not been suspected before. Bound by their deep-rooted religious convictions, and by a background of philosophy that did not include invisible forms of life, these early microscopists could not bring themselves to believe in the things that moved beneath their lenses. Life on a microscopic scale was not to be considered; the creatures that were seen through the microscope must be manifestations of the Divine will—or of evil spirits. They arose by spontaneous generation, the outcome of some mysterious vital force. It remained for the brilliant Italian, Lazaro Spallanzani, to explode these theories in the late eighteenth century, showing that the world of micro-life was a world in which birth, life, and death followed their familiar pattern.

The excitement that accompanied the discovery of a micro-world stimulated development of the microscope itself. Lenses in the early instruments were made by pressing blobs of molten glass into curved hollows in charred wood. These crude lenses were full of imperfections; the discovery that lenses could be ground to accurate shape subsequently brought immense improvements in instrument design.

During the eighteenth century microscopes were built in which the lenses were drops of water. Some were made from sapphires and rubies and other precious stones. The nineteenth century saw great development in both the optical and mechanical design of the microscope, and by 1825 microscopes were being manufactured for sale. Prior to that date, if you wanted a microscope you made one.

Even by 1847 there were only four microscopes in New York City.

The tremendous advances made in science during the last hundred years could not have been made without the microscope. Modern medicine is based upon the ideas of germ-caused disease worked out by Koch and Pasteur as a result of what they saw through their microscopes. The form of the standard optical microscope has changed little since it became a mass-produced instrument. But within the last few years great strides have been made in microscopy with the discovery of new techniques that can overcome some of the deficiencies of the ordinary instrument.

In the normal way objects are viewed in a microscope by shining light through them. Often the objects are transparent to most of the light and it is difficult to make out the different features that we wish to see. Thin slices of living tissue, for example, are almost invisible under the microscope. In order to bring out differences in the structure of transparent materials of this sort special stains are used which are absorbed more readily by some parts of the tissues than by others. Staining techniques have helped us to find out much of what we know about the microscopic structure of living things.

Staining, however, has its drawbacks. It will often destroy or damage the tissue that we are examining. And new techniques have been devised for viewing objects which are normally difficult to make out from their surroundings.

Dark-field illumination, for example, enables us to see transparent droplets of oil floating as an emulsion in equally transparent water. Light is passed through the emulsion in such a way that it does not enter the lens directly at all. If there was nothing but pure water under the microscope nothing would be seen through the eyepiece; all the light shines past the lens. But, when the water contains oil droplets, light passing through the emulsion is scattered by the droplets so that some of it is diverted and

enters the lens of the microscope. We can see the droplets shining as bright globules in a dark field.

One of the latest techniques for viewing completely transparent specimens is called phase-contrast microscopy. This technique, which has developed since World War II, has become of the very greatest importance in the study of living tissue. Some of the light passing through the specimen is scattered and follows a different path from the rest of the light. One of the beams is passed through a greater thickness of glass than the other, so that the wave vibrations in the two beams are 'out of step.' When the beams are combined the image forms by interference.

In one way and another the modern microscope has become a versatile and extremely powerful optical instrument. But it has been realized for a century and more that there is a limit to what a microscope can do. This limit is set by the light waves themselves, and nothing we can do in the way of refining the optical microscope can get over the difficulties.

There is no limit to the magnification that we can get with a microscope. We can always increase the sheer size of a picture simply by enlarging it to whatever dimensions we want. But what really counts is the microscope's ability to render the fine detail visible. This is the resolving power of the instrument; its efficiency in separating two fine dots placed close together.

No matter how powerful a microscope may be, it will not be able to distinguish between two points on any object if they are separated by less than half the wave-length of the light being used in the instrument. When yellow light is used, for example, with a wave-length of about twenty-two-millionths of an inch, the smallest 'resolvable' distance is about ten-millionths of an inch.

To increase the performance of the microscope it can be used with light of the smallest possible wave-length, extending even into the ultra-violet region. With the shortest ultra-violet light that can conveniently be used it is

possible to reduce the resolvable distance to about five-millionths of an inch. The image cannot be seen directly in ultra-violet light, but it can be photographed. This is the absolute limit of the ordinary optical microscope. To penetrate any further into the fine structure of a specimen it is necessary to use even shorter waves than ultra-violet. That means using, for example, X-rays.

Since 1912, when the wave nature of X-rays was discovered, scientists have been trying to make X-ray microscopes. For years the idea was abandoned as there were no suitable substances from which to make lenses that would bend X-rays in the way that glass bends light. But new techniques were developed during World War II, and by 1948 X-ray microscopes had been made with a resolving power of thirty-millionths of an inch.

By 1954 the General Electric Company of America had developed an X-ray microscope with a useful magnification equal to the best optical microscope. Instead of showing a conventional image, it looks inside the object and magnifies the internal structure that is hidden when ordinary light is used.

The X-ray microscope works on a simple principle. It throws an enlarged shadow of the object in the rays from a tiny source. In ordinary light a mammoth shadow of a hand is cast on a wall by a lighted candle held near the hand. The sharpness of the shadow depends on the size of the light-source; the bigger the light is the more blurred is the edge of the shadow. Also the nearer the light is to the hand, and the further the wall is from the hand, the bigger the shadow will be.

The successful production of the X-ray microscope has resulted from the discovery of methods of producing X-rays from an incredibly small source. A conventional X-ray source cannot be made smaller than about an eighth of an inch in diameter. But in the G.E.C. X-ray microscope it is only one-hundredth-thousandth of an inch—300 times smaller than the width of a human hair.

The X-ray microscope is still in the stage of early development, but it is already becoming an invaluable scientific instrument. Using waves 10,000 times shorter than those of visible light, it could distinguish between points on an object less than three ten-millionths of an inch apart.

In the early 1930's it was found that beams of electrons travelling at great speed have properties similar to waves. They can be bent and focused by passing them through electromagnets and can in this way be controlled like ordinary waves of light. The electromagnets act as lenses.

Attempts were made to build microscopes which used electron beams in place of light, and during World War II the electron microscope was developed with immense success. By 1947 it had reached a resolving power of three hundred-millionths of an inch. It has carried us into the realm of individual atoms and molecules.

The optical microscope can reach a useful magnification of about 2000; but the electron microscope can magnify things by 100,000 times and more. With its help we can study bacteria in detail and see what happens inside the smallest cell. We can photograph the tiny virus particles of diseases such as poliomyelitis which are too small to be seen in ordinary visible light.

When Zacharias Janssen invented his microscope at the end of the sixteenth century he stimulated interest in the use of lenses for other purposes as well. If light could be bent and focused so that tiny invisible objects became large enough to see could it not also be controlled to enable man to see things far away? Janssen himself designed a simple instrument of this sort, and may have been the inventor of the telescope. But it seems more likely that the credit belongs to another spectacle-maker in the same Dutch town of Middelburg, Hans Lippershey.

Lippershey is reputed to have made his discovery accidentally; he was carrying a spectacle lens in each hand and happened to look through both of them held in line with

the church steeple. To his amazement he found that the weathercock on the steeple appeared to have been moved nearer to him. Hurrying to his workshop, Lippershey fitted the two lenses into a long tube and so made the first telescope. Like Janssen's microscope, the telescope caused great excitement in the scientific world, and instruments were soon in widespread use all over Europe.

In May 1609 Galileo heard about the new invention during a visit to Venice. Soon he had made a telescope for himself and was concentrating all his energies on improving the design of the instrument. He increased the magnification of his telescopes from three to thirty-three and used them enthusiastically in the exploration of the stars.

Galileo discovered that the sun had spots and that Jupiter had satellites. He mapped the mountain ranges of the moon and studied the movements of the planets in the solar system. So famous did Galileo become as a result of his discoveries with the telescope that his name has always been associated with its invention. Even to-day the tvpe of telescope he used is called a Galilean telescope; it was, in fact, designed by Lippershey.

Like the microscope, the telescope has developed steadily up to the present time. As efforts were made to increase the magnification the barrel of the telescope grew longer. In 1655 a twelve-foot telescope discovered Titan, one of Jupiter's satellites. By 1672 another satellite had been seen with the help of a thirty-five foot instrument, and in 1684 two more were discovered with telescopes that focused the light 136 feet from the lens. Even this was not enough. Telescopes were made in which the focus was 200 yards from the lens. The enormous length of these early telescopes was a result of the inherent deficiencies of a simple lens in dealing with visible light. The spherical-surface lens brought light passing through its outer regions to a different focal point than light passing through the central area. Also, the lens of the telescope, like any other

simple lens, bends every constituent wave-length of the light through different angles. As in the microscope, these faults brought light to an indistinct focus; the effect was minimized by using a lens that focused its image as far away as possible.

In 1758 John Dollond discovered the achromatic lens, consisting of a combination of two lenses of different types of glass. Each glass caused a different amount of 'spread' of the different wave-lengths in visible light, the combined result being to minimize the divergence of the colours in the light.

Improvements in lens design have partly overcome other faults that mar the performance of a lens, and the refracting telescope—in which light is brought to a focus by being refracted or bent in lenses—has made steady progress to this day. The largest telescope of this type has a lens with an effective aperture of forty inches diameter. It is owned by the Yerkes Observatory in the United States.

As astronomers seek to penetrate further into space there is a demand for telescopes with ever-larger apertures. The bigger the lens, the more light the instrument can collect and focus, so that yet fainter stars may be seen. But the manufacture of lenses becomes increasingly difficult as the size goes up. Casting a glass lens that will be of uniform transparency and free from faults limits the size that can be made in practice; even if lenses bigger than our present largest were successfully cast, they would tend to deform under their own weight and their ability to focus accurately would be diminished.

The refraction of visible light as it leaves one transparent medium and enters another has given us many invaluable optical instruments based on the lens. But in two of the most important, the microscope and the telescope, the lens has apparently reached a point where it can advance still further only with extreme difficulty.

15

A Mirror on the Universe

REFLECTION was recognized as a fundamental property of light by the Greek philosophers. They understood the geometrical precision with which the rays of reflected light behaved. As it bounced back from a reflecting surface, they observed, a ray of light made the same angle with the surface as did the original ray.

Some surfaces, like a highly polished metal, will reflect almost all the light that falls on them. Mirrors are made by coating a smooth sheet of glass with a thin film of mercury or silver. This reflects the light so accurately that we see an image of ourselves returned to us by the mirror.

Reflection of this sort is possible only when the reflecting surface is regular and smooth. The light that strikes the surface is treated uniformly and the reflected rays behave in ordered fashion. But if the reflecting surface is rough and pitted a ray of light is reflected in a direction that depends on the inclination of the surface of the bump or hollow that it meets. A piece of white paper reflects light in this way. The surface is a good reflector in that it returns much of the light that strikes it. But the light is scattered in all directions by the tiny irregularities on the surface.

When a ray of light falls on to the smooth surface of a mirror the direction in which the reflected ray returns depends upon the angle at which we set the mirror. If the light strikes perpendicularly it returns along the route by which it came. The more we turn the mirror, the bigger is the angle between the two rays. By controlling the angle

of the mirror we can control the direction in which the light travels. Reflection can therefore be used for concentrating light in the same way that refraction is used in a lens.

In order to focus the light that strikes a lens the surface of the glass is curved so that light striking any part of the surface is bent towards the focal point. In the same way light striking the surface of a mirror can be focused by curving the mirror into the shape of a shallow dish. Each part of the mirror's surface reflects the light that strikes it towards a definite point in front of the mirror. Light coming from every point on an object can be focused to a corresponding point in front of the mirror, forming an image similar to that thrown by a lens.

Curved mirrors used in this way have several advantages over ordinary lenses; in particular, a mirror brings light of any wave-length to the same focal point. Light reflected by a mirror does not have to travel through any medium other than the air; it is not refracted, so that there is no separation of the light into its constituent wavelengths.

When telescopes were being extended to fantastic lengths in order to try and minimize the effect of this separation of light Sir Isaac Newton realized that the difficulty could be overcome by using mirrors instead of lenses. Newton carried out many experiments, which culminated in the invention of the reflecting telescope. The mirrors were made from a highly polished alloy of copper and tin.

Light entering Newton's telescope was focused by a curved mirror. But before coming to a focus the light struck a small flat mirror placed in the centre of the tube at an angle of forty-five degrees. This mirror reflected the rays so that they emerged through an eyepiece in the side of the telescope.

Modifications have been made to the design of the reflecting telescope since Newton's day, and it has progressed from strength to strength. Nowadays the mirrors

of reflecting telescopes are usually made from glass discs ground to shape and then coated with a film of silver or aluminium. The world's largest telescopes are all of the reflecting type. Biggest of all is the giant Hale telescope on Palomar Mountain, in California, which came into operation in the autumn of 1949.

This telescope, with its 200-inch diameter mirror, is named after George Ellery Hale, the astronomer who conceived it during the late 1920's. Until 1949 the biggest telescope was a 100-inch reflector on Mount Wilson nearby.

The project to build a 200-inch telescope was officially announced on October 29, 1928. The California Institute of Technology undertook the immense task of building the instrument, aided by a grant of six million dollars from the Rockefeller-endowed General Education Board. Work began immediately on the huge mirror which was to form the heart of the telescope, and on the equipment that would carry and manœuvre the mirror as it searched the sky.

The giant mirror was to be made from glass, ground and polished so that its surface was saucer-shaped. A thin layer of aluminium was then to be applied to act as the mirror proper; light striking the metal would be reflected towards a point near the top of the telescope ' tube.'

The job of making the mirror was undertaken by the Corning Glass Works, of New York. Casting a slab of glass of this size to the accuracy needed was something that had never been done before, and a great deal of experimental work had to be carried out before an attempt could be made to cast the mirror itself.

If the mirror had been cast in the form of a solid slab of glass it would have weighed about forty tons and the glass would have sagged under its own weight as it was tilted. Also, the mirror would be for ever changing its shape under the effect of temperature changes in the air. Glass is a bad conductor of heat, and the flow of heat between a thirty-inch-thick slab and the air would have been so slow that

the mirror would need about two days of steady temperature to allow its surface to settle down uniformly. Even with the most efficient circulation in the observatory, a telescope is subject to constant changes of temperature as the night air enters through the open roof. A thick slab of glass would take so long to adjust itself to these changes that the telescope would be out of action most of the time.

Experimental mirrors were made from quartz, which expands and contracts much less than glass as the temperature changes. Quartz mirrors two feet in diameter were made successfully, but larger ones raised practical difficulties that could not be overcome.

Early in 1932 Pyrex glass was substituted for the quartz. Although this glass expands and contracts more than quartz, its reaction to temperature changes is very much less than ordinary glass. To reduce the effect of temperature changes to a minimum a special design was worked out. The face of the mirror was to consist of a slab of glass four inches thick, and this would be supported by four-inch thick ribs of glass forming a honeycomb structure on the under side. Every part of the slab would be in close contact with the circulating air, and no part of the glass would be more than two inches from the air. It was anticipated that this design would allow the mirror to adjust itself to the temperature of its surroundings in a short time. Also it reduced the weight of the mirror to slightly less than fifteen tons.

After overcoming immense difficulties the Corning Glass Company succeeded in casting a 120-inch disc with the honeycomb structure. Then a larger mould was constructed, and on March 25, 1934, the first attempt was made to cast a 200-inch disc. But the cores of the mould forming the honeycomb broke loose and floated on the top of the glass.

Cooling devices were then installed in the cores, and on December 2, 1934, a 200-inch disc was cast successfully. It was kept hot at a steady temperature so that strains set

up in the glass could ease themselves; then the glass was allowed to cool slowly for a further eight months. Tests carried out on the cooled disc showed that it was comparatively free from internal strains.

On March 20, 1936, the giant slab of glass, the largest ever cast by man, set out on its journey over 3000 miles of the United States to Pasadena, in California. Its journey completed, it disappeared into the optical laboratories of the California Institute of Technology; here it remained for four years as the face of the slab was ground and polished into the gently curved, saucer-like shape that was needed. Five tons of glass were removed from the disc hollowing the surface to a depth of three and three-quarter inches in the centre. This formed a spherical surface. Then by grinding away another one-twentieth of an inch in the centre the mirror was given its final paraboloid shape.

In 1942 the war brought work on the telescope to a halt for three years. But in 1945 the polishing was resumed, and by 1947 the concave surface of the mirror was pronounced perfect to within one-millionth of an inch. It focused light falling on its surface at a point fifty-one-and-a-half feet in front of it.

Supporting the giant mirror was in itself an almost superhuman undertaking. The fifteen-ton slab of glass had to be carried so that it could be swung into position to receive the light from any desired part of the sky. Held at the base of its 'tube'—in fact, a skeleton steel framework—the mirror shines its light to a focus near the top of the tube; here, in the middle of the tube itself, a tiny laboratory was built, where the picture thrown by the mirror can be photographed.

The entire moving structure of the telescope when completed weighed some 450 tons. It is carried on bearings floating on a film of oil the thickness of cigarette paper, and is poised so delicately that the whole structure will move under the weight of a packet of sandwiches placed on one of the beams.

So rigid is the framework of the telescope 'tube' that the little laboratory situated at the focal point moves only a fraction of an inch out of alignment as the immense structure swings from one part of the sky to another.

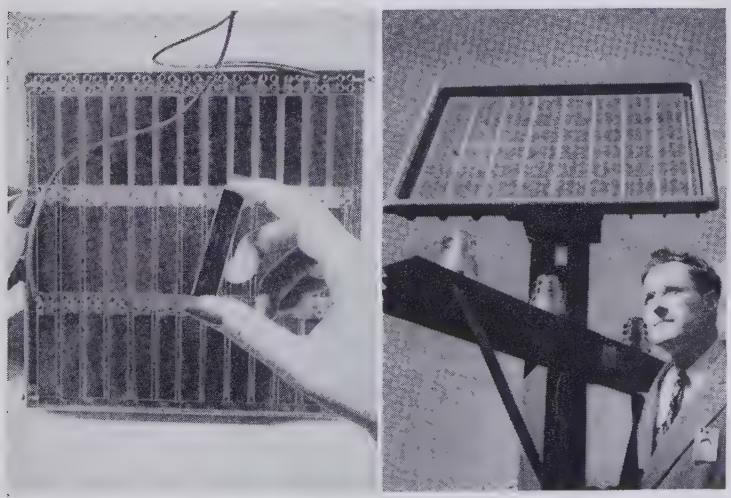
The block of curved glass sitting in the base of the telescope mounting is in fact only the support for the mirror proper. Once the surface of the glass disc had been hollowed out accurately it was coated with a film of aluminium a two hundred-thousandth of an inch thick. This layer of aluminium protects itself from corrosion by reacting with the oxygen of the air; a transparent film of aluminium oxide is formed which cuts off further contact between the metal and the air.

The giant mirror of Palomar is really a film of metal weighing less than half a crown. The light it reflects is recorded on a photographic emulsion which is itself only a thousandth of an inch thick. These two films, which between them weigh only an ounce or two, are the essential parts of the Palomar Telescope. All the rest of the structure, the huge girders and bearings, the electronic controls and the motors, the fifteen-ton glass disc, and the floating laboratory are incidental equipment that enables the astronomers to manœuvre and control the movement of the aluminium mirror and the photographic plate with respect to the stars in the sky.

Since it was officially dedicated in June 1948 the 200-inch telescope has been modified and improved in many ways. Most of the teething troubles have been overcome; some have yet to be solved. The honeycomb glass disc adjusts to the temperature of its surroundings in little more than an hour, compared with the two days that a solid disc would have needed. During the twenty years that elapsed between the start of the project and the completion of the telescope improvements in technique and materials were incorporated with outstanding success. The telescope is roughly twice as efficient as it would have been if it had been completed in 1930.

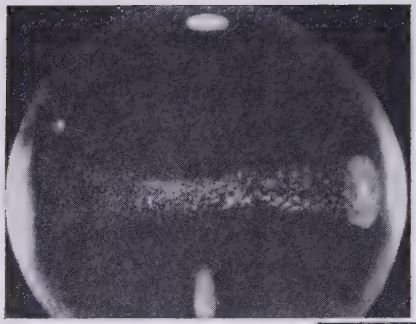
BELL SOLAR BATTERIES

(Left) Operating a small mobile radio transmitter by means of a Bell solar battery
(Right) Transmitting a telephone conversation by the same means



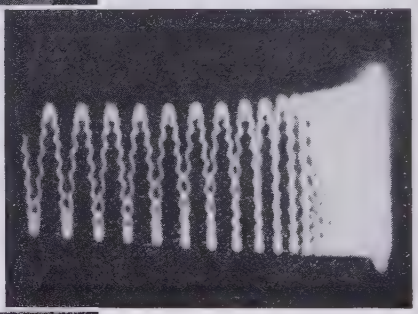
Photos Bell Telephone Laboratories

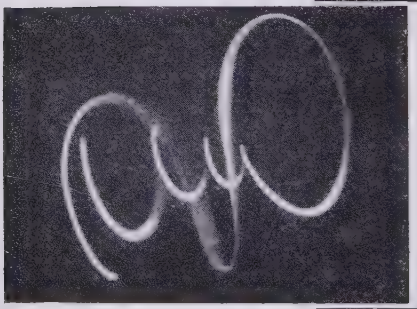
(Left) A solar battery, showing silicon strips
(Right) A model of the battery, mounted on a section of telegraph pole



A beam of sunlight is shining through this glass flask from left to right. Air has been pumped out, leaving a vacuum. A shake, and little particles of graphite start spinning round the beam of light. So long as the light shines the particles rotate.

When the beam is steadily weakened the spinning particles move towards the focus of the light, tracing out a spiral path.





Sometimes they cavort and whirl in strange, fantastic shapes. Like this . . .

. . . or this. Why do they do it? Nobody knows.

Photo "Discovery"

PHOTOPHORESIS

The 200-inch mirror of the Hale telescope collects four times as much light as the 100-inch telescope on Mount Wilson. This latter telescope was the largest in the world until the Hale telescope was built. The main function of the 200-inch mirror is to increase the brightness of the image that we can seek out from the sky. It improves the resolving power available to astronomers, rather than giving increased magnification. Stars that appear as indistinct blobs of light in smaller telescopes are seen as groups of many separate stars.

The ability of the huge mirror to collect and concentrate light enables the astronomer to peer still farther into outer space. Stars sending out light so faint that we cannot see them with smaller telescopes can be detected by the Hale instrument. The 200-inch reflector has enabled us to penetrate so far into space that astronomers now have eight times as large a universe in which to carry out their explorations as they had before.

It is impossible for us to comprehend the distances travelled by light that reaches us from these far-away stars. Even with the 100-inch reflector we could detect stars so distant that the light from them has been travelling for 500 million years. And at a speed of 186,000 miles a second light covers quite a distance in this time!

With the 200-inch telescope we can pick up light that has been on its way for a thousand million years. The photographs we take are recording events that happened in the universe long before man appeared on earth. The 200-inch mirror can gather as much light as a million human eyes. If the curvature of the earth did not get in the way it could 'see' a flashlamp shining from Land's End.

This extreme sensitivity of the 200-inch telescope has given astronomers an instrument that they can bring to bear on some of the outstanding problems of their science. By prying farther into space than has been possible before the Hale telescope may help us to understand the mystery

of the expanding universe. Huge nebulae, consisting of luminous systems of stars and gas, appear to be moving away from us at speeds as great as 60,000 miles a second.

Light coming from far-distant nebulae, split into its component wave-lengths in a spectroscope, shows typical dark bands caused by absorption of certain wave-lengths as the light has passed through substances on its way. Photographs taken of these spectra thrown out by different nebulae have shown that the wave-lengths of the light are often shifted towards the red end of the spectrum. This is an indication that the nebula is moving rapidly away from us; the waves of light are ' stretched out ' by the movement of the source.

This ' red shift ' has been studied intensively by astronomers for more than thirty years. It has been found that most of the nebulae are moving away from us, but a few show a ' blue shift,' indicating that they are moving towards us. The amount of the ' red shift ' in the majority of nebulae depends on their distance from the earth; the farther away they are, the faster they are retreating.

Until the Hale telescope came into operation our study of these fast-moving nebulae was restricted to those within the 500 million light-year reach of the 100-inch telescope. But now we can carry the investigation to those nebulae up to a 1000 million light years away. Nebulae 360 million light-years away have been shown to exhibit a ' red shift ' corresponding to a speed of 38,000 miles a second.

Although the ' red shift ' can be explained on the basis of this rapidly expanding universe, some astronomers have suggested that light may simply be losing energy as it travels on its immense journeys through space. This would mean that the wave-lengths of the light become longer and longer as the journey continues, and light showing a ' red shift ' could in fact be coming from a stationary star.

One of the other fundamental problems to be tackled by large telescopes is the measurement of the size of the universe. By counting the nebulae in far-distant regions of the

sky the Palomar astronomers will be able to get a more accurate sample of the star content of the sky. It will be possible to estimate the size of the universe more accurately than before.

Big telescopes, by collecting more of the light that is coming from a star, enable us to analyse the light with greater accuracy. The spectroscope can separate light into its constituents, providing a clue to the elements that are present in a star. To reap the full reward of light-analysis we must have an adequate amount of light. A large telescope can therefore tell us more about the nearer stars by providing plenty of light for analysis; it can also collect enough light from faint, far-distant stars to provide the astronomer with material for study.

The 200-inch Hale telescope has captured the fancy of a size-conscious public, and there has been a tendency to over-value it in comparison with other smaller instruments. Undoubtedly the 200-inch telescope is the most exciting one of all; the mere fact that it can penetrate farther into space than can other telescopes gives it a superior dramatic appeal. But size is not the only criterion of value in an optical instrument, least of all a telescope. There are many other superb telescopes in the world, all of which are contributing to our understanding of the universe.

California is fortunate in having the finest collection of telescopes in the world, all working together and each contributing what it is best fitted to do. The Palomar Observatory was built and is owned by the California Institute of Technology, and the Mount Wilson Observatory, including the 100-inch telescope that has been doing such fine work since 1918, belongs to the Carnegie Institute in Washington. Since the 200-inch Hale telescope came into operation in 1949 both observatories have been operated administratively as a team. Research headquarters is situated at the California Institute of Technology, 127 miles from Palomar.

In 1948 a second telescope was completed and joined the 200-inch Hale telescope on Mount Palomar. This instrument, housed in a separate observatory, is neither a reflector nor a refractor, but a bit of both. It is a Schmidt telescope, in which mirrors and lenses are combined to enable astronomers to photograph the sky to great depths and over comparatively large areas. The 'Big Schmidt' on Mount Palomar carries a 76-inch mirror and does not have the penetrating power of its 200-inch companion. But it can survey much more of the sky at one time than can the Hale telescope, and the two are able to work together as a team.

The Hale telescope probes deeply into the sky but gives us an extremely narrow field of view; it is like an oil prospector's drill that bores deep into the earth. But the Big Schmidt tells us what is happening over bigger regions of the sky at any time; it is more like a quarrying operation that uncovers several acres of rock deep down in the earth.

This type of telescope was designed by the German astronomer Bernhard Schmidt, of the Hamburg-Bergedorf Observatory. It overcomes some of the deficiencies inherent in both reflector and refractor instruments. The early refractor telescopes, which used lenses to focus light, were built to enormous lengths to cut down the effects of light-separation by the lens. Then the achromatic lens was discovered, and lens telescopes became less unwieldy. But really big achromatic lenses raise all sorts of difficulties.

In the large modern telescopes the change-over to mirrors has solved the problem of light-separation. Defects of a spherical mirror have been overcome by shaping the mirror into a parabola, as in the Hale telescope. But even so, light entering the telescope at an angle to the central axis is not focused accurately and the field of view of the mirror telescope is extremely narrow. Big telescopes gather a lot of light, but they have to collect it from a tiny area of the sky.

Schmidt designed his telescope on an entirely new principle. He went back to the spherical mirror and put a special thin lens in front of it. This lens altered the directions of the light rays before they struck the mirror, so that after they had been reflected they would come to an accurate focus from all parts of the field of view.

Schmidt built his first telescope to this design in 1930; it had a fourteen-inch lens and a seventeen-inch mirror. He found that the instrument gave an excellent field of view over a comparatively large area of the sky. The defects of the spherical mirror used alone were overcome, and the image was of first-rate quality. Schmidt's instrument was really a camera rather than a telescope. The image, instead of being viewed in the usual way or photographed on a flat plate, was photographed on a special spherical plate.

During the 1930's several Schmidt-type telescopes were built, the largest being a thirty-inch mirror instrument at the Mexican National Astrophysical Laboratory.

In 1938 the California Institute of Technology decided that a large Schmidt telescope would make an invaluable partner to the giant Hale instrument. During the following year construction of a 76-inch mirror telescope began. It came into operation nine years later.

The Big Schmidt can penetrate about one-third as far as the 200-inch reflector, picking up light that has been on its way for 300 million years. It set to work without delay and has been engaged on the ambitious project of carrying out a systematic survey of the entire sky. In this way the Schmidt telescope acts as a scouting patrol for the 200-inch telescope, seeking out interesting regions of the sky into which the giant instrument can probe.

The instruments grouped around Mount Wilson and Palomar form an astronomical team without equal in any other part of the world. But new telescopes are being built that will all play their part in the immense tasks that are still to be done as we try to unravel the mysteries of space.

At Pretoria, in South Africa, a 74-inch reflecting telescope, biggest in the Commonwealth, is seeking out information from the southern sky. It has been estimated that astronomy in the southern hemisphere is half a century behind astronomy in the northern hemisphere. The Pretoria telescope, together with a 74-inch reflector at the Commonwealth Observatory of Australia, at Canberra, will provide much needed information from the southern skies.

It is unlikely that optical telescopes will be built in the future with reflectors greater than the 200-inch one at Palomar. This limit has been set, not by the technical difficulties involved but by the effect of atmospheric conditions.

The new telescope at the Royal Greenwich Observatory at Herstmonceaux, in Sussex, is to be a 98-inch instrument; a French telescope at Saint-Michel, near Marseilles, is of 76-inch diameter, and an observatory at Helwan, in Egypt, has a 74-inch instrument.

The largest telescope to be built since the Hale telescope came into operation is a 120-inch reflector that will give California yet another giant instrument. With the veteran 100-inch telescope on Mount Wilson this will mean that California has the three largest telescopes in the world.

The 120-inch reflector belongs to the University of California and is housed at the Lick Observatory on Mount Hamilton. Here it will join a famous family of instruments that has been making history since 1888. The 36-inch refractor at the Lick Observatory is the second largest of its type and has been peering into the sky for more than half a century.

The heart of the 120-inch reflector, a four-ton Pyrex disc, was acquired by the University at bargain basement price. It was cast in 1933 for testing the 200-inch mirror of the Hale telescope, but another method of testing was adopted and the huge glass disc was never used. For nearly twenty years it lay in a cellar in Pasadena. It was sold to the University of California at cost price.

With the help of the experts who built the 200-inch telescope, the Lick Observatory scientists have made the 120-inch mirror into the heart of a telescope that is the most up-to-date in the world. The size of the tiny cage carried at the focal point in front of the mirror has been cut down and the cage reshaped; in this way only a little more than one-tenth of the light that would otherwise reach the mirror is cut off. The Lick telescope will penetrate into realms of the sky reached only by the Hale telescope. It will collect light that has travelled for 900 million years on its way from luminous bodies in outer space.

These fantastic achievements in our exploration of space have been made possible by controlling the reflection of light from mirrors shaped to direct the light rays to the point at which we want them. Just as this method of focusing light has enabled us to build more powerful telescopes than we can with lenses, so has it provided a method of overcoming some of the difficulties that have held up development of the optical microscope.

At the University of Bristol a novel type of microscope has been built by Dr C. R. Burch, using curved mirrors instead of lenses to control the light. The reflecting microscope is not affected by the wave-lengths of the light in which the specimen is viewed. There are no lenses to bend light of different wave-lengths through different angles. A specimen focused in yellow light remains in focus in ultraviolet light.

With these and other advantages to recommend it, the reflecting microscope is becoming as important in the development of microscopy as the reflecting telescope has been in astronomy. Mirrors are coming into their own in opening up the world immediately around us, as well as the worlds that lie in the outer regions of space.

16 Power from the Sun

EVERY second of every day the sun is turning more than four million tons of its matter into energy. This is the energy that radiates into space in all directions from the surface of the sun. A very small fraction of it reaches us here on earth, bringing us the mixture of radiations we recognize as sunshine.

As they reach the outer layers of the earth's atmosphere, the sun's radiations cover a wide range of wave-lengths. At one end of the scale there are short, invisible ultra-violet rays, and at the other end the long infra-red rays, which we cannot see but are able to feel as heat. It is now known that the sun is also sending out even longer radiations in the form of radio waves.

The range of waves in our sunlight is cut down at each end by the atmosphere of the earth. The shortest ultra-violet rays are absorbed in the upper stratosphere, where they excite the atoms of atmospheric gases, detaching electrons from them to leave electrically charged ions. This is the region of the ionosphere, the electrically sensitive layer or series of layers from which radio waves are reflected back to earth. When too much ultra-violet light is pouring into the ionosphere, at times of great sunspot activity, the electrical activity is so great that radio waves can penetrate and disappear into space. Ultra-violet light from disturbances on the sun is the cause of radio black-outs.

At the other end of the sunshine-radiation range the long-wave, infra-red rays are absorbed by dust and mois-

ture in the lower levels of the atmosphere. These invisible rays help to warm the air in which we live.

The sunlight that reaches the earth, therefore, consists essentially of visible light with a restricted range of invisible rays at each end of the spectrum; some ultra-violet rays remain just outside the short-wave end and some infra-red rays remain beyond the long-wave end. This is the mixture of radiations that carries a continuous supply of energy from the sun to the earth.

We depend entirely upon this energy for everything that adds up to life and civilization. Energy is not a tangible thing, like matter. It is a mysterious 'something' that powers the universe. It drives the complex engine of the living machine; in the form of heat it warms our homes and cooks our food, boils the water in factory power-houses, and expands the gases in a motor car engine. Light itself is energy carried by ether waves of certain length; electricity is a form of energy that 'flows' like an invisible liquid through the cables that carry it all over the world.

The sun is the source of all the energy we use on earth. In days gone by sunshine was stored up as energy in the chemicals forming the substance of living things. Great forests flourished when the world was young; the vegetation died and was buried beneath layers of rock, and the once-living matter was heated and compressed and turned into coal.

In the same way countless millions of tiny marine organisms lived and died, and their tiny corpses collected on the sea bed. Squeezed by thick layers of sediment and stone, the body materials were transformed into oil.

To-day we make use of these residues of once-living things as sources of energy. By burning them we release the sunshine that was stored away when they lived in far-distant days. Coal and oil are capital reserves of energy from the sun.

In wood we have a store of sunshine energy laid down in more recent times. By burning wood we are releasing

sunshine energy that shone on to the earth only a few years ago. And in agricultural crops we have energy-stores that were built up by plants within a single season. This is the energy we release inside our bodies when we eat plant substances as food.[1]

Today we are relying more and more upon water as a source of energy and power. Water collects in the reservoirs high in the hills, driving our turbines as it rushes down towards the sea. The energy of high-level water is energy from sunshine that has reached the earth only weeks or perhaps days before we use it. This sunshine has evaporated water from the sea and carried it off as vapour over the land. Here the water has fallen as rain on the high ground; packed into it is energy absorbed from the sunshine that lifted it from sea-level high into the hills. This is the energy the water hands over to the turbine, which in turn translates it into electrical energy in the dynamo.[2]

The world is now needing more and more energy. There are more people to be fed, and more factories to run; there are more planes and ships, cars and engines, to push about the earth. Energy is needed on a prodigious scale, and the demand is rising from year to year. The average consumption of food by each person on earth amounts to about 2500 calories per day; but the average consumption of energy for other purposes is 25,000 calories per day—ten times as much.

At the present time we depend very largely on the long-stored sunshine of coal and oil for our energy supplies. But these capital reserves will not last for ever. In many countries we are using energy stored more recently in the form of wood fuel, or water-power. Attempts are being made to draw energy from the wind.[3]

But there are limits to the extent to which these sources of energy can be used. In Africa and some other parts of

[1] See *The Fight for Food.*
[2] See *The World of Water.*
[3] See *Our Astonishing Atmosphere.*

the world water-power resources are still virtually unused; elsewhere we have tapped almost all the supplies that are available. The wind, at best, can provide only small amounts of energy compared with the needs of the world as a whole.

Superimposed on this increasing demand for more energy on a world-wide scale, there is an immediate need for energy supplies in regions where natural resources are few. In the dry regions of Africa and Australia, in the Middle East, Pakistan, and India, and in parts of the United States and South America, there are vast areas of land where nothing grows. Almost one-third of the total land area of the earth is under-developed. And to bring it into cultivation two things are needed above all—water and energy.

If these arid and neglected lands could be brought to life they would provide much-needed food for the mounting population of the world. Given a bountiful supply of cheap energy, water could be brought to them and power provided to maintain life.

Unfortunately many of the arid zones of the world are devoid of the stored fuels, the wood, and the hill water that could release the energy which is so badly needed. The cost of transport is so great that fuel becomes too expensive when brought from afar; electricity networks are prohibitive when long distances have to be covered to reach thinly scattered populations. To bring these under-developed regions alive we must make use as far as possible of the daily rations of energy delivered by the sun.

Encouraged by UNESCO, countries with this immediate interest in developing new sources of energy have been co-operating in an attempt to harness the sunshine which is so often lavished on the arid regions of the earth. Sunshine is the world's energy income, rather than its capital. When all the coal and oil and fissionable materials have gone we shall have to rely upon the sunshine as our energy

source. The problem that is being tackled by underdeveloped countries now is part of a world problem that must be solved by man in centuries to come.

It is strange that we have done so little to try and harness the enormous flow of energy that reaches us every day from the sun. We go to immense trouble and cost to bring the coal and oil we need from the earth. We spend hundreds of millions of pounds in developing atomic energy. Yet, every day, the earth is presented with sunshine containing as much energy as we would get from 500,000 million tons of coal.

Even in the United States, where more energy is used per person than in any other country, this daily supply of sunshine is 2000 times as great as the amount of energy that is consumed. If we could harness even a modest fraction of it, sunshine could run all our factories and mills, heat our homes, and drive our cars and trains and ships.

Up till now man has made little headway in his efforts to make direct use of energy from the sun. In theory the solution would seem to be a simple one; but in practice it is much more difficult than it appears. For centuries we have used the sun's energy in a few relatively unimportant ways. The ingenious engineers of ancient civilizations used it to open their temple doors. From Biblical times the sun has been evaporating water from salt-pans on the edges of tropical seas. But apart from a few such incidental uses we have been content to let the sunshine concentrate on growing our food for us; the rest of it has largely been left to go to waste. Some of the sunshine that reaches the earth's surface is reflected; it disappears into space, carrying its energy away for ever. The rest is absorbed, and several things can happen to it.

As the streams of radiation pour into the rocks and soil, the water, and vegetation of the earth's crust the vibrations of the molecules of these substances are stimulated. They become warmer, and, after holding briefly to their extra energy, the molecules emit it again. But the size of the

energy bundles has changed; the waves have become longer and are now infra-red rays which we cannot see but can feel as heat.

This transformation of the short waves of visible light into heat is a fundamental process in the world's use of solar energy. It is the basis of some of the earliest and most efficient of the methods now being devised for harnessing sunshine.

The greenhouse is a device that makes use of sunshine in this way. Visible light flows through the transparent glass and beats on to the plants and earth of the greenhouse floor. It is absorbed, causing a rise in temperature as the vibrations of the molecules increase. Then, longer infra-red waves are emitted by the warm earth and plants, which would carry the excess energy away into space. But glass is opaque to these invisible heat rays. They are trapped inside the greenhouse; the warmth is retained where it is needed.

The use of sunshine as a source of heat is the basis of most efforts being made to develop the large-scale application of solar energy. Usually sunshine from a large area is collected with the help of curved mirrors or lenses, so that its energy can be concentrated by focusing the rays. As long ago as 1818 a twenty-square-yard reflector was concentrating the sun's rays on to a boiler at the Paris Exhibition; it generated one horsepower.

A pumping engine used for irrigation in Cairo before World War I was driven by steam raised in a sunshine furnace. Rows of huge mirrors shaped like troughs focused the sunshine on to water pipes running down the centre of each trough.

Similar sunshine engines were built between the wars in Australia and Mexico, some of them raising as much as fifty horsepower. But even in these sunny countries, where a reasonably steady supply of sunshine could be relied upon, the mirror-type machine did not progress beyond the experimental stage. Construction of the mirrors was

a costly business, and sunshine had to be collected from too large an area when a powerful engine was needed.

Since World War II new techniques have revived scientific interest in sunshine-collecting machines of this sort. Huge parabolic mirrors can be made more cheaply; aluminium-coated plastics, for example, can be moulded easily into accurately-shaped mirrors.

Great interest has been taken by French scientists in the mirror-type solar machine. In 1946 Felix Trombe built a solar furnace near Paris, using mirrors six feet in diameter. Sunshine brought to a focus by these mirrors was able to produce temperatures of 3000°C.—high enough to melt such refractory materials as lime.

The success of these early experiments has led to the construction of an enormous mirror engine at the 300-year-old fort of Mont Louis in the Pyrenees. Here, at a height of 5000 feet above sea-level, the air is clear and the sun shines bright for 2750 hours of every year.

Heart of the giant installation at Mont Louis is a 33-foot diameter parabolic mirror made up of 3500 separate small mirrors. Sunshine is thrown on to this concave mirror by a flat reflector consisting of more than 500 plate-glass mirrors; controlled by photoelectric devices, the mirror follows the sun as it moves across the sky. As the sunshine comes to a focus from the huge concave mirror it shines on to a small furnace to produce temperatures of 2500°C. Bars of metal and slabs of other high-melting substances can be melted in large quantities at a time. A 100-lb. block of iron is liquified in less than an hour.

Even higher temperatures are raised by smaller sun-engines which concentrate the sunshine in mirrors from former German searchlights. The production of high temperatures in this type of solar furnace is of great scientific interest on its own account. Substances can be heated almost instantaneously to thousands of degrees without any contamination from other chemicals. A ten-foot aluminium mirror built at Rockhurst College, in

Kansas City, reached 3000°C. in ten seconds. It was used to study metals and other materials at temperatures such as those experienced in jet engines.

In Algeria a parabolic mirror reflector twenty-seven feet in diameter is being used by Professor A. Guillemonat to unite the oxygen and nitrogen of the air, forming nitrogen oxides. Nature does the same thing with the help of the high temperatures produced in the lightning flash; this is a source of much of the soil's natural nitrate fertilizer.

Russia, with more than a million square miles of arid territory and a quarter-million square miles of desert, is showing great interest in the development of solar energy devices. A thirty-foot parabolic mirror at Tashkent is raising 130 lb. of steam an hour at 100 lb. to the square inch pressure. Similar machines are distilling salt water to provide fresh water from the brackish lakes of the Kara Kum desert; this water is used by sheep and cattle that graze on the sparse, dry pastures.

These large solar energy devices may in due course become of immense value for providing power in isolated regions of the world. They could not compete with coal and oil under ordinary conditions; even in sunny countries the area of mirror needed to provide power in large quantities is too great. Also, the sun is an intermittent energy source; at night or on a dull day the solar engine comes to a halt.

But where alternative and more convenient fuels are not available mirror-machines can provide energy where there would otherwise be none.

This application of the mirror as a sunshine concentrator is becoming important as a source of energy for domestic use. In India millions of people find difficulty in getting enough fuel of any sort to cook their food. Coal and oil are scarce; trees are too precious to cut down for wood. Cooking is often done over a fire made from dried animal dung; but this dung would be better used as a fertilizer on the land.

Yet in India there is no shortage of sunshine; energy in abundance beats down on villagers who cannot find enough to cook a pot of rice.

At the National Physical Laboratory in New Delhi Indian scientists have devised a mirror cooker that is cheap and simple enough to be mass-produced and distributed to Indian peasants. An aluminium reflector, nearly ten square feet in area, concentrates sunshine on to the bottom of a pan held on a platform in the centre of the mirror. At midday, when Indians eat their main meal, the sun produces about 350 watts. A kettle containing three-quarters of a gallon of water can be boiled on the solar stove in less than an hour. There is a market for at least 100 million of these cookers in India.

Although curved mirrors are needed to focus sunshine in order to raise high temperatures, they are not necessary if the heat is being used at relatively low temperatures. Houses, for example, are heated only a few degrees higher than the outside temperature to make them comfortable. And the sun's energy can be used effectively for this purpose.

An ordinary glass window is the simplest of all sun traps. Light flows through the glass, but long-wave heat rays cannot flow out by the same route. In the sunnier regions of the United States thousands of houses are warmed by sunshine falling on water-pipes on the roof. Heat is collected in the pipes and carried around the house.

The drawback to these simple, straightforward sunshine heaters is that they work best when heat is least needed. To make them really effective they need some system of storing heat when the sun is shining, so that it can be released at night when the sun goes down.

Dr Maria Telkes, of Massachusetts Institute of Technology, devised a heat storage system that has operated successfully in experimental houses for several years. Sunshine is absorbed by black metal plates in a south glass wall and the heat carried by an air stream to storage bins

containing Glauber's salt. This chemical liquefies as it takes up heat from the warm air. But as the air cools down at night the Glauber's salt solidifies and releases the heat again. One cubic foot of Glauber's salt can store eight and a half times as much heat as water when its temperature is raised from 80° to 100°F.

The first house using this type of storage heater was built at Dover, Massachusetts, in 1948. It cost more than £10,000, of which £1000 was spent on the solar heating system. The storage bins held more than twenty tons of Glauber's salt.

In countries where coal and oil are comparatively cheap the capital cost of these solar heating installations is too high to make them popular. But large-scale production could reduce the cost and bring them into widespread use. Even in a temperate climate the roof of an average house receives 400-500 times as much energy from the sun as is used for domestic purposes. There is ample 'fuel' for the solar heaters, and it is all free.

Sometimes light falling on a substance will detach electrons completely from their parent atoms. These liberated electrons flow as an electric current, so that light can be transformed directly in this way into electricity.

In 1955 scientists at Bell Telephone Laboratories developed a solar battery which uses sunlight as a direct source of useful amounts of electricity. The heart of the solar battery consists of wafers of silicon; as sunlight falls on this element a current of electricity is stimulated large enough to light a lamp or power a midget radio transmitter. The extraordinary thing about this solar battery is its comparatively high efficiency. It converts as much as a tenth of the sunlight falling on it into electricity. This is a high rate of exchange for devices of this sort.

The silicon battery operates on the energy supplied by visible light rather than on the long-wave, infra-red heat rays. It will therefore go on generating electricity even on cold days when the sky is overcast. One square foot

of surface covered with silicon wafers will generate enough electricity to light a ten-watt bulb.

The silicon used in solar batteries must be extremely pure, and refining it is a costly business. There is no prospect at the present time of using silicon batteries on a really large scale. But already they are being put to practical use.

Silicon batteries are providing current for amplifying telephone signals. Fixed to telephone poles, the batteries absorb sunlight during the day and deliver an electric current. Some of the current is stored in accumulators to be used during the night when the silicon battery stops working.

There is no way of telling whether silicon batteries will be able to provide electric current on a really big scale from sunlight in the future. It seems probable that we shall use silicon to help us generate free electricity for our homes. Ten square yards of silicon plates taking the place of roofing tiles could provide the electricity needed by an average household.

Although these solar furnaces, sunshine-heated homes, and solar batteries are occupying so much of our scientists' time to-day, we have been making intensive use of sunshine energy for thousands of years by the most familiar process of all. Every green plant that grows on earth is maintaining its life and providing food for animals by using sunshine to manufacture the complex living substances of its body. Photosynthesis—synthesis with the aid of light—is going on continuously inside the green cells of all plants. With the help of chlorophyll, the green pigment that gives plants their characteristic colour, carbon dioxide and water are turned into the sugars that are the basic raw material of the plant world. Packed into this sugar is a supply of sunshine energy that has enabled the chemical transformation to take place. This energy is released inside the living tissues of the plant to power the processes of life. When plants are eaten by animals as food the energy of

these same substances is released to serve the living animal body.

Sunshine is, in this way, the source of all the energy involved in life. In plants we have Nature's own solar-energy machines; the light absorbed by green cells is held as chemical energy in the substances of the plant body. Although Nature is able to capture the sun's energy so easily, she does it inefficiently. Only a small amount of the sunshine reaching a field or plantation is used effectively by the plants that grow there. Often the proportion is as low as one-half per cent.

In our efforts to find a way of using sunshine to the best advantage we could well begin by stepping up the efficiency of Nature's own chlorophyll-controlled processes. This must be done if we are to provide enough food energy for the millions of extra human beings that appear in the world each year.[1] But we could use fast-growing plants as well to provide us with all the additional energy we need.

Wood is an expensive fuel to gather and handle, but it can be converted easily into liquid fuels and gas. Much could be done to increase our returns of stored sunshine by extending the forest-lands of the world. Timber from three million square miles of forest, an area as big as the United States, could provide the world's present energy requirements indefinitely. As fast as trees were cut down others would be growing to take their place.

In under-developed countries the increased use of wood as a fuel could bring immediate returns in the way of greater efficiency in the use of available sunlight. In India, for example, the bullock is a peasant's normal source of power. The efficiency of the bullock, measured by comparing the mechanical energy it provides with the amount of food it eats, is about 5 per cent. For every 400 watts of power it gives, the animal eats thirteen and a half tons of food a year. But this same return of power could be

[1] See *The Fight for Food.*

provided by a small steam engine using six tons of eucalyptus wood as fuel.

Although the steam engine is so much more efficient by direct comparison with the bullock, the latter is more adaptable under peasant farming conditions. On the other hand the engine consumes its fuel only when it is working; the bullock eats whether it is doing any work or not.

Despite the difficulties, there is every reason to believe that by ' mechanizing ' peasant agriculture with the help of wood-burning steam engines we could harness large quantities of solar energy that are now allowed to run to waste. If they did nothing else these engines could pump irrigation water and drive the light machinery that is so much a part of modern farming.

If engines of this sort were used for irrigation only 2 per cent. of the land they served would be needed to provide the wood they used as fuel.

Although wood has many advantages as a fuel, it is comparatively slow in growing. Sunshine can be packed into tropical vegetation that grows quickly during a single season. The sugar in sugar-cane, for example, can be used directly as a fuel without waiting millions of years for it to be turned into coal. Even to-day sugar cane could give us a fuel costing only a few times as much as coal. Grown deliberately as a fuel, it could become much cheaper than it is.

Research carried out in India has shown that sugar cane is one of the most efficient plants with respect to the amount of sunshine that it uses. It captures 2 per cent. of the radiation that is available to it during the growing season. Sorghum is almost as good, with 1·76 per cent.; rice makes use of 1·17 per cent. of its sunshine and wheat only 0·44 per cent.

Even at best, therefore, these traditional crop plants are inefficient solar machines. They do not compare with the small one-celled algæ which form the floating pastures of the sea. Some types of alga are reported to be able to cap-

ture as much as 15 per cent. of the sunshine that reaches them. Algæ can be grown on a continuous basis and will convert carbon dioxide into more complex substances so long as there is sunshine available to them. The energy stored in these substances can be released by using algæ as food; or it can be liberated as heat if the algæ are burned as fuel.

For years efforts have been made to divorce the process of photosynthesis from the living cell of the plant. Chlorophyll is a chemical which brings about a chemical reaction in converting carbon dioxide and water into sugars. There is no reason why we should not be able to carry out this same reaction in the laboratory. But so far nature has held fast to the secrets of her manufacturing process. The day has not yet come when we shall trap the sunshine reaching a chemical factory and store it in the form of synthetic chemicals that can be used as fuels.

Meanwhile chemical processes of other types are being studied with a view to making use of sunshine energy. Lawrence J. Heidt, of the Massachusetts Institute of Technology, discovered a method of using sunlight to split water into its constituent gases hydrogen and oxygen. The element cerium, dissolved in water, absorbs light energy as it jumps backward and forward between two different atomic states. As it does so the cerium liberates hydrogen in jumping one way and oxygen in jumping the other way. The energy absorbed from the sunlight is stored in the two gases that come bubbling from the decomposed water. When the gases are recombined by burning the hydrogen in oxygen sunlight energy is made available to us as heat.

The efficiency of this process in its early stages was extremely low—only one-tenth of 1 per cent. of the absorbed light was converted into chemical energy. But with more research it should be possible for this water-splitting process to become an economically important way of harnessing the sunlight. One advantage of using sunlight in bringing about a chemical change is that the energy is

stored as chemical energy in the manufactured substance. The energy is available for use whenever it is needed. When sunlight is being turned into electricity, on the other hand, the energy produced cannot be stored efficiently for use when the sun goes down.

It is impossible to predict accurately the amount of energy that the world will be using a hundred years from now. Between 1900 and 1950 our annual energy requirements increased by a half. And the rate of increase is still being fully maintained. It is reasonable to assume that by 2050 sunshine will be providing at least as much energy as we are now deriving annually from coal, oil, water, and other sources.

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Light travels Fast

To-day we accept without thought the fact that our sunshine has covered great distances by the time that it reaches the earth. Light is something that moves. Yet 300 years ago, scientists were still arguing whether light appeared instantaneously or travelled at enormous speed from one place to another.

The great Galileo, during the early seventeenth century, experimented with light to try and support his belief that it travelled at a definite speed through the air. Two men were stationed three miles apart, each with a lamp. The first man uncovered his lamp and started a clock. As soon as the second man saw the light he uncovered his lamp. Then, when the first one saw the light from this second lamp, he stopped the clock.

Galileo hoped that this experiment would give him a measure of the time taken for the light rays to travel twice the distance between the two men. But he found that the time did not change appreciably, no matter how far the two men were apart.

Galileo's experiment failed, not because light materialized instantaneously, but because it travelled too quickly. We now know that light moves at about 186,000 miles per second; it would cover the return trip between Galileo's two men in less than one thirty-thousandth of a second. This is thousands of times smaller than the time taken for a man to detect the light, come to a decision, and perform an action such as stopping a clock.

In 1676 Olaf Roemer, a young Dane living in Paris, astonished the French Academy by announcing that he had measured the speed of light. Roemer noticed that the eclipses of four of Jupiter's satellite moons took place at the wrong time; they were either too early or too late compared with the calculated times that they were due. Roemer showed that these fluctuations were caused by the varying distances between Jupiter and the earth. Light had to travel journeys of different lengths; when the journey was a long one the light arrived late, and when it was a short journey the light arrived too soon.

Roemer worked out from what he knew of astronomical distances that light was taking eleven minutes to cover the radius of the earth's orbit. It was travelling at about 120,000 miles a second.

With light travelling at such a speed, little could be done in those days to measure it accurately on the earth itself. And it was left to the astronomers to study the speed of light as it covered enormous distances in space. In 1728 the English astronomer Bradley found that some stars were not always where calculations said they ought to be. While yachting on the Thames Bradley found a clue to this unusual astronomical behaviour by watching the pennant fluttering at the mast-head. Every time the boat changed its course the pennant flew in a different direction, even though the direction of the wind had not changed. It was being affected not only by the wind but by the movement of the boat as well.

Bradley realized that the relative movement of the earth and stars were upsetting his calculations of the positions of the stars in the sky. Light had to be considered as something travelling with a definite speed through space in order to put things right. So Bradley confirmed the theory put forward by Roemer; he worked out that it took eight minutes twelve seconds for light to reach the earth from the sun; it travelled, he calculated, at 187,000 miles per second.

This figure for the speed of light is very close to the speed we recognize to-day. But throughout the eighteenth century it was impossible for a definite speed of light to be worked out and accepted generally. Astronomical distances were not known with sufficient accuracy, and as a result there were several values for the speed of light, varying round and about the figure of 190,000 miles per second. It was up to the individual scientist to take his choice.

During the early nineteenth century science was making rapid progress, and finding a really accurate speed for light became a matter of urgent importance. Two French scientists ran a neck and neck race to devise light-measuring instruments that could be used without reference to other worlds outside the earth.

The race was won by A. H. L. Fizeau in 1849. In Fizeau's apparatus light shone on to the edge of a wheel with 720 teeth. As it passed through a gap between the teeth the light travelled to a reflector five miles away, from which it returned to the edge of the wheel.

When the toothed wheel was revolved a speed was reached at which the reflected light could not be seen through the edge of the wheel. By the time the light had made its journey from the gap between two teeth to the reflector and back again, one of the teeth was in the way. So by measuring the speed of the wheel it was possible to estimate how long the light had taken on its ten mile journey. Fizeau worked out that light travelled at 195,000 miles per second in air.

A year later another French scientist, Foucault, published the results of his light-measuring experiments. In place of a toothed wheel, Foucault used a mirror that could be rotated 800 times a second. Light was shone on to the mirror and reflected on to a reflector about four yards away. By the time the light returned to the mirror from the reflector the mirror had moved very slightly, so that it threw an image slightly to one side of the light source. By

measuring the deflection Foucault calculated the speed of light at 185,000 miles a second.

Foucault's apparatus had the great advantage of being small. The light travelled distances of only a few yards, instead of miles, so that it was possible to measure the speed of light in substances other than air. Foucault found that, in water, light travelled slower than in air. According to the particle theory of light, it should travel faster in water than in air, whereas if light consisted of waves it should travel faster in air than in water. Foucault's experiment therefore gave immense support to the wave theory of light.

In the hundred years that have passed since these two Frenchmen first measured the speed of light on earth their techniques have been refined and adapted. A. A. Michelson, a German scientist who became a United States citizen, used a rotating glass octagon to determine the speed of light with an accuracy much greater than Foucault was able to do with his mirror. Michelson, who was awarded a Nobel Prize in 1907, spent many years trying to determine the speed of light. His figure of 186,271 miles per second was eventually accepted in 1935, after his death.

During the late 1930's the speed of light became of immense importance in the world of science. It is a fundamental figure in Einstein's Theory of Relativity.

According to Einstein, the speed of light in a vacuum is a fixed, unchanging constant. It is the greatest speed possible in the universe; anything faster than this speed is a meaningless figure. As an object approaches this speed of light its dimensions shrink in the direction of travel. At 161,000 miles per second it would appear to be half its normal length. Similarly any time-device, such as a clock or the ordered processes of the human body, would run at only half the normal rate.

Any object moving at the speed of light would have infinite weight; a rocket travelling through space as fast as light would weigh as much as the universe itself. In fact

nothing but light itself can move at the speed of light.

During World War II the speed of light became of great practical importance. The operation of radar depended on being able to measure the distance travelled by radar waves reflected from enemy planes and ships. An accurate knowledge of the speed of the radar waves—that is, the speed of light—was needed in order to calculate the distance they travelled as they bounced back to the transmitter.

During wartime work on radar a British physicist, Dr Essen, had misgivings about the accuracy of the figure that had been generally accepted for the speed of light. He re-examined and re-assessed the research that had previously been done and decided that there was room for doubt. Using modern radio techniques, he carried out accurate measurements of electro-magnetic wave-speeds. The speed of light in a vacuum was found to be 186,282 miles a second. Michelson's value for the speed of light, which had previously been used in physical calculations, was eleven miles a second too slow.

This most up-to-date value for the speed of light has enabled radar to be used with greater accuracy than before and has affected calculations that form the basis of modern physics.

When light falls on to an object we can imagine countless billions of tiny particles storming along at colossal speed and battering against the surface that they meet. The momentum carried by these fast-moving particles should enable the light to exert a pressure. This pressure has now been detected and measured.

More than fifty years ago a Russian physicist, Peter Lebedev, suggested that the pressure of light could explain the mystery of a comet's tail. Comets are solid bodies that revolve about the sun in long-drawn-out orbits. When they are moving near to the sun they throw out streams of gas that trail along in the form of the familiar comet's tail. But this tail does not, as might be supposed, flow out behind

the comet as it rushes along. The tail is thrown out so that it is always on the side opposite the sun. It is as though a great wind was blowing on the comet from the sun, forcing the gas away to leeward.

Lebedev believed that the comet's tail was blown outward by the pressure of radiation from the sun, and he carried out researches to measure the pressure exerted by light.

Lebedev made use of the difference in pressure exerted against reflecting and absorbing surfaces. If a charge of buckshot, for example, is fired against a board, the board is pushed back by the force of the pellets as they embed themselves in the board. But if the pellets bounced off at the same speed as they hit it the board would be subjected to twice as much pressure.

When light particles strike a black surface, they are all absorbed; that is why the surface appears black. But when they strike a reflecting surface, such as a mirror, they are bounced off again. And the pressure exerted against a reflecting surface is twice as great as it is against an absorbing surface.

If a delicately mounted paddle-wheel is made with one side of its paddles black and the other reflecting, light will exert a greater pressure against the reflecting side than against the black surface. The wheel will therefore revolve.

Lebedev used an instrument built on the paddle-wheel principle to measure the pressure of light. Instead of allowing a paddle to turn freely he suspended a little pair of paddles on a fine fibre, so that light shining on them tended to twist the fibre. By measuring the twisting force exerted on the fibre, Lebedev could calculate the pressure of the gas striking the paddles.

Although the principle was simple enough, the experiment proved difficult in practice. If the paddle was suspended in an apparatus filled with air the heat of the sunshine caused convection currents which disturbed the paddles. But if air was pumped out of the vessel the few

remaining air molecules would heat up as they bumped against the hot vanes of the paddle; shooting off at great speed, they would kick the paddle backward and so exert pressure against it.

In spite of the difficulties, Lebedev managed to carry out his measurements of the pressure of light. He was able to confirm that a reflecting aluminium surface was pushed back with almost twice the pressure of a light-absorbing surface coated with platinum black. Two American scientists, Nichols and Hull, carried out similar experiments and confirmed Lebedev's discovery that the pressure exerted by light was the same for rays of any colour. It amounts to about 30 lb. on a square mile of the earth's surface.

This tiny pressure exerted by the sunshine reaching the earth is much too small to be felt by us in any significant way. But in the play and interplay of cosmic forces in the universe it is of some account.

In spite of its insignificance from an earthly point of view, the pressure of light is powerful enough to spin a rotor moving with a minimum of resistance from friction. Professor J. W. Beams, at the University of Virginia, carried out experiments with small rotors held in space and spun by magnetic forces. These rotors, suspended freely without any bearings, can be spun so fast that they explode under the terrific centrifugal force developed. Spinning in a vacuum, the only friction that plays on them is caused by the few remaining gas molecules. A rotor spinning at 100,000 revolutions per second will 'coast' for an hour and lose only a thousandth of its original speed.

Professor Beams calculated that the pressure of light directed against the outside edge of a rotor of this sort would be powerful enough to overcome this slight frictional resistance. Experiments have shown that a rotor is, in fact, accelerated by light 'fired' against it in this way.

Although this pressure exerted by light is simple enough to understand, there is a phenomenon connected with it that remains an unsolved mystery. This is the movement

of small particles in opposite directions when a beam of light falls on them. Some particles move away from the source of the light, as might be expected if pressure is exerted on them; others, however, move towards the source of the light as though they were being attracted by it.

This phenomenon, called photophoresis, was discovered during the 1920's by a Viennese physicist, Professor Felix Ehrenhaft. It has never been satisfactorily explained. Some scientists claim that the movement of the particles is caused by currents set up in the air or other gas that surrounds them. But Ehrenhaft has claimed that photophoresis takes place even when the particles are in a vacuum. When the direction of the light is reversed the movement of the particles is reversed too.

Research on photophoresis has complicated the phenomenon even more; small particles can now be made to revolve in orbits round a beam of light. Graphite dust in an evacuated bottle will revolve round a beam of light shone through the bottle like moths buzzing round a candle flame. If the direction of the beam is changed the orbits of the particles remain perpendicular to it. And as the strength of the light alters the orbit moves to different distances from the point where the light beam is focused. When the light becomes weaker the rotating particles move near to the focus; as the light becomes stronger they move away from it. By reducing the light gradually the particles can be made to move in a spiral orbit as they edge towards the focus of the rays. Eventually the orbit moves across the focus to the other side, until the light becomes too weak to keep the particles in movement.

The actual paths followed by particles rotating round a beam of light are extremely complex. As they make their way in an orbit round the beam the particles are at the same time tracing a spiral path round this orbit. The path they follow is like a coiled spring bent in a circle round the beam of light. And in addition, the particles spin rapidly

like miniature tops at speeds as high as 4000 revolutions a second.

Often there are variations on this orbit pattern, the particles tracing out strange whorls and convolutions under the influence of the light. The force that keeps them going has been calculated at more than fifty times the force of gravity.

Superimposed upon the major mystery of photophoresis, there are smaller ones that complicate the issue. Why do some particles gyrate, whilst others fall to the floor of the flask? Why do some move one way and others in opposite directions?

Photophoresis is a phenomenon that is still full of mystery to us. It is a reminder of how little we really know about the waves-cum-particles that we recognize as light.

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